Source: NIST

Figure 6–34. Three-workstation fire test, 2 min after the start.

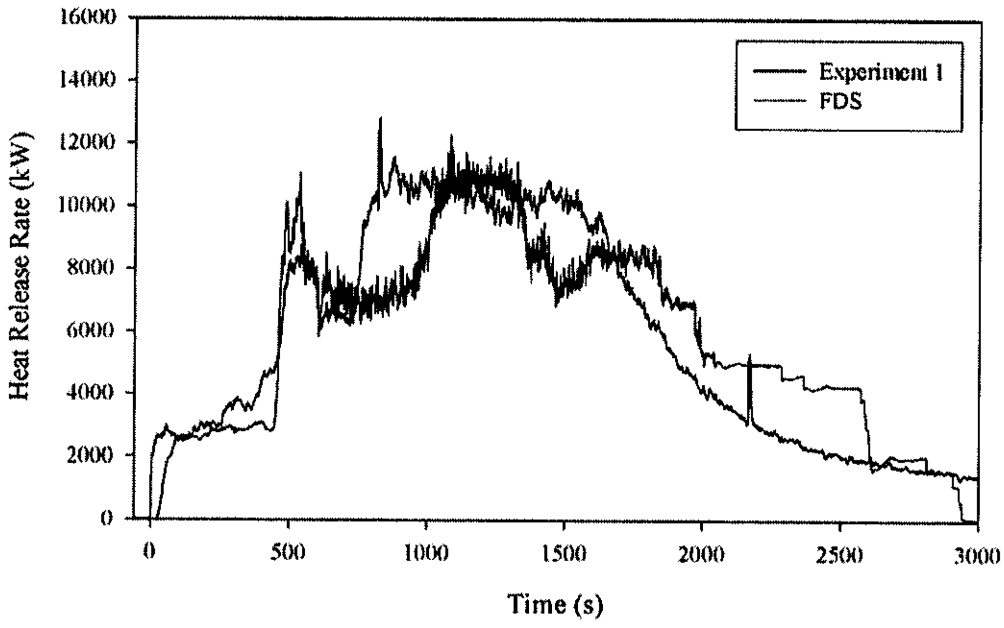


Figure 6–35. Measured and predicted heat release rate from the burning of three office workstations.

The differences in the fire behavior under the different experimental conditions were profound in these roughly hour-long tests. The jet fuel greatly accelerated the fire growth. Only about 60 percent of the

combustible mass of the rubblized workstations was consumed. The near-ceiling temperatures varied between 800 °C and 1,100 °C. Nonetheless, FDS successfully replicated:

- The general shape and magnitude of the time-dependent heat release rate.
- The time at which one half of the combustion energy was released to within 3 min.
- The value of the heat release rate at this time to within 9 percent.
- The duration of the fires to within 6 min.
- The peak near-ceiling temperature rise to within 10 percent.

All these predictions were within the combined uncertainty in the model input data and the experimental measurements.

Combined, these results led to the assessment that the uncertainty in the thermal environment predictions of the WTC fires would be dominated less by the FDS errors and more by the unknowns in such factors as the distribution of the combustibles, ventilation, and building damage.

6.10.3 The Four Cases

Four fire scenarios (Case A and Case B for WTC 1 and Case C and Case D for WTC 2) were superimposed on the four cases of aircraft-driven damage of the same names (Section 6.9).

A number of preliminary simulations had been performed to gain insight into the factors having the most influence on the severity of the fires. The most influential was the mass of combustibles per unit of floor area (fuel load); second was the extent of core wall damage, which affected the air supply for the fires. The aforementioned workstation fire tests had also indicated that the damage condition of the furnishings also played a key role. The scenario variables and their values are shown in Table 6–6.

Table 6–6. Values of WTC fire simulation variables.

Variable	WTC 1		WTC 2	
	Case A	Case B	Case C	Case D
Tenant combustible fuel load[a]	4 lb/ft^2	5 lb/ft^2	4 lb/ft^2	5 lb/ft^2
Distribution of disturbed combustibles	Even	Weighted toward the core	Heavily concentrated in the northeast corner	Moderately concentrated in the northeast corner
Condition of combustibles	Undamaged except in impact zone	Displaced furniture rubblized	All rubblized	Undamaged except in impact zone
Representation of impacted core walls[b]	Fully removed	Soffit remained	Fully removed	Soffit remained

a. In addition, approximately 27,000 lb of solid combustibles from the aircraft were distributed along the debris path.
b. In Cases A and C, the walls impacted by the debris field were fully removed. This enabled rapid venting of the upper layer into the core shafts and reduced the burning rate of combustibles in the tenant spaces. In Cases B and D, a more severe representation of the damage was to leave a 4 ft gypsum wallboard soffit that would maintain a hot upper layer on each fire floor. This produced a fire of longer duration near the core columns and the attached floor membranes.

FDS contained no algorithm for breaking windows from the heat of the fires. Thus, during each simulation, windows were removed at times when photographs indicated they were first missing. Damage to the ventilation shafts was derived from the aircraft impact simulations. For undamaged floors, all the openings to the core area were assumed to total about 50 ft^2 in area.

6.10.4 Characterization of the Fires

For each of the four scenarios, FDS was used to generate a time-dependent gas temperature and radiation environment on each of the floors. The results of the FDS simulations of the perimeter fire were compared with the fire duration and spread rate as seen in the photographs and videos. For ease of visualization, contour plots of the room gas temperature 1.3 ft below the ceiling slab (in the "upper layer" of the compartment) were superimposed on profiles of the photographed fire activity. An example is shown in Figure 6–36. The stripes surrounding the image represent a summary of the visual observations of the windows, with the black stripes denoting broken windows, the orange stripes denoting external flaming, and the yellow stripes denoting fires that were seen inside the building. Fires deeper than a few meters inside the building could not be seen because of the smoke obscuration and the steep viewing angle of nearly all the photographs.

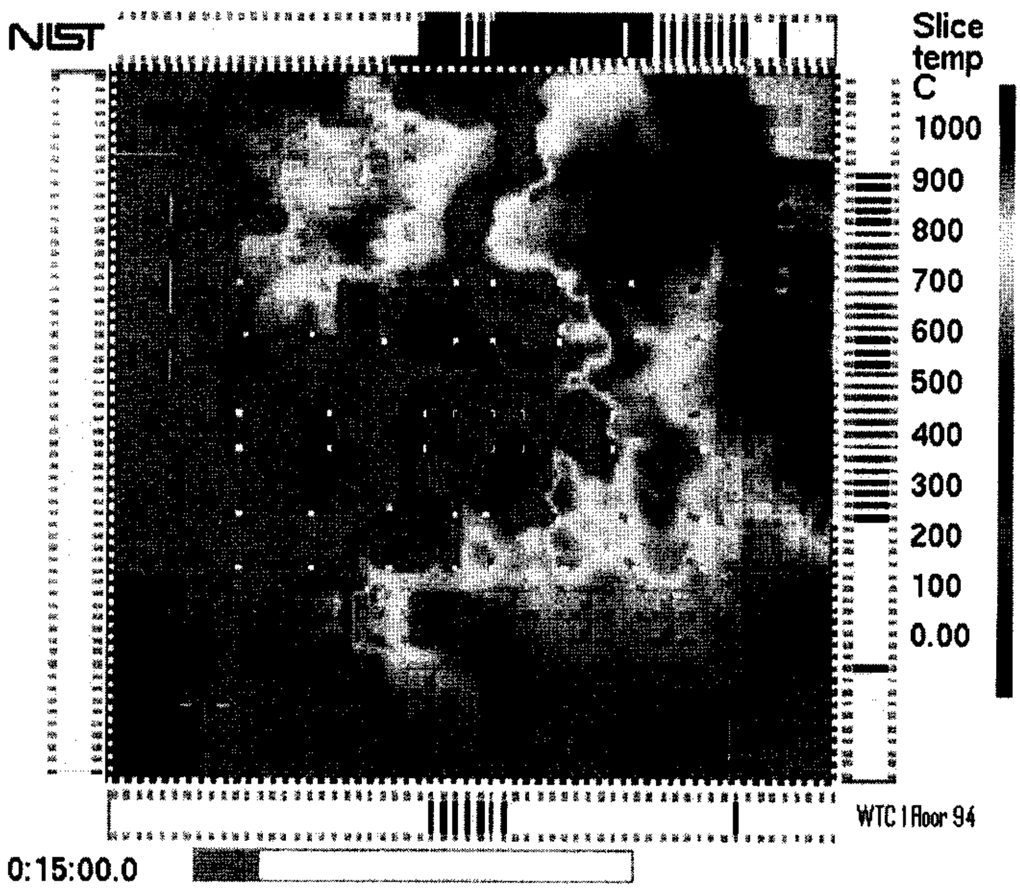


Figure 6–36. Upper layer temperatures on the 94th floor of WTC 1, 15 min after impact.

Given the uncertainties in some of the floor plans, the damage to the internal walls, and movement of the office furnishings, the intent of the simulations was to capture the magnitudes of the fires and the broad features of their locations and movement; and they did so.

The following sections summarize the simulated behavior of the fires (which was used in the following stages of the disaster reconstruction) and their correlation with the analysis of the photographic evidence.

WTC 1

Much of the fire activity was initially in the vicinity of the impact area in the north part of the building. As a result of the orientation of the impacting aircraft and its fuel tanks, the early fires on the 92nd through 94th floors tended toward the east side of the north face, while the early fires on the 97th through 99th floors tended toward the west side of the north face. The fires on all the floors spread along the east and west sides and were concentrated in the south part of the building at the time of collapse, as depicted in Figure 6–37.

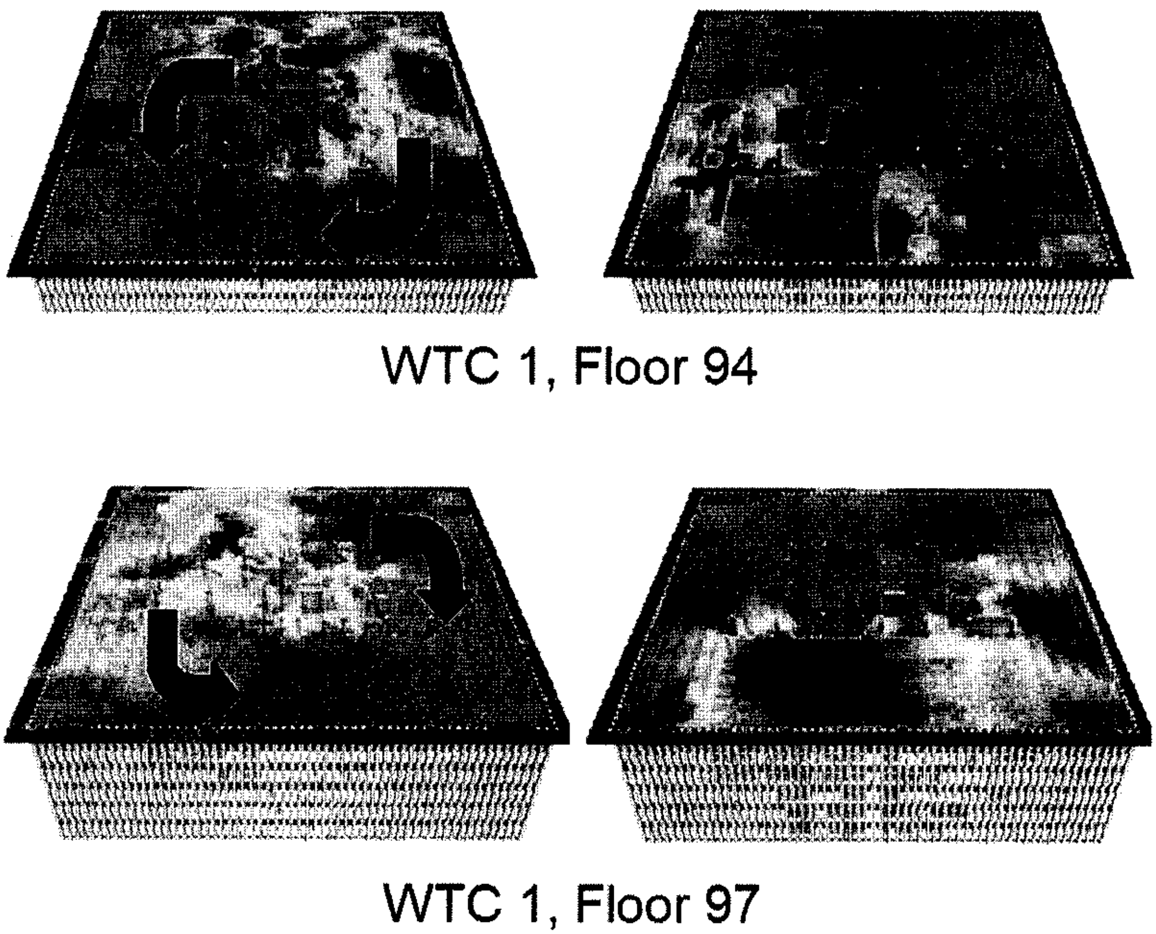


Figure 6–37. Direction of simulated fire movement on floors 94 and 97 of WTC 1.

The fire simulation results for Case A and Case B were similar, indicating only a modest sensitivity to the fuel load and the degree of aircraft-generated damage. This was because, in general, the size and movement of the fires in WTC 1 were limited by the supply of air from the exterior windows. Since the window breakage pattern was not changed in Case B, the additional and re-distributed combustibles within the building did not contribute to a *larger* fire. The added fuel did slow the spread slightly because the fires were sustained longer in any given location.

Although there was generally reasonable agreement between the simulated and observed fire spread rates, there were instances where the fires burned too quickly and too near the windows. This resulted from an artifact of the model: the combustible vapors burned immediately upon mixing with the incoming oxygen.

Simulations performed with doubled fuel loads slowed the fire spread well below the observed rates. Combined with the above results, this suggested that the estimated overall combustible load of 4 lb/ft^2 was reasonable.

The simulations showed high temperatures in some of the elevator shafts. The late fire observed on the west face of the 104th floor may have started from fuel gases in the core shafts that had accumulated over the course of the first hour of fires below. The presence of fire in the shafts on the 99th floor provided some support for this hypothesis, but no simulations were performed for floors higher than the 99th.

The predictions of maximum temperatures (e.g., red zones in Figure 6–37) were consistent with those in the three-workstation fire tests.

The use of an "average" gas temperature was not a satisfactory means of assessing the thermal environment on floors this large and would also have led to large errors in the subsequent thermal and structural analyses. The heat transferred to the structural components was largely by means of thermal radiation, whose intensity is proportional to the fourth power of the gas temperature. At any given location, the duration of temperatures near 1,000 °C was about 15 min to 20 min. The rest of the time, the calculated temperatures were near 500 °C or below. To put this in perspective, the radiative intensity onto a truss surrounded by smoke-laden gases at 1,000 °C was approximately 7 times the value for gases at 500 °C.

WTC 2

Simulating the fires in WTC 2 posed challenges in addition to those encountered in simulating the fires in WTC 1. The aircraft, hitting the tower to the east of center, splintered much of the furnishings on the east side of the building and plowed them toward the northeast corner. Neither the impact study nor the validation experiments performed at NIST could be completely relied upon to predict the final distribution, condition, and burning behavior of the demolished furnishings. In addition, only the layouts of the 78th and 80th floors were available to the Investigation; the other floors were only roughly described by former occupants. As a result of these unknowns, the uncertainty in these calculations was distinctly greater than in those for WTC 1. To help mitigate gross differences between the simulations and the observables, NIST made floor-specific adjustments, based on the results of preliminary computations. In particular, the fuel load and volatility on the 80th floor were reduced, and the fuel load on the 81st and 82nd floors was increased.

In contrast with WTC 1, in WTC 2 there was less movement of the fires. The major burning occurred along the east side, with some spread to the north. There was no significant burning on the west side of the tower.

Also unlike WTC 1, changing the combustible load in WTC 2 had a noticeable effect on the outcome of the simulations. Because so many windows on the impact floors in WTC 2 were broken out by the aircraft debris and the ensuing fireballs, there was an adequate supply of air for the fires. Thus, the burning rate of the fires was determined by the fuel supply. In the Case D simulation, the office furnishings and aircraft debris were spread out over a wider area, and the furnishings away from the impact area were undamaged. Both of these factors enabled a higher burning rate for the combustibles.

In general, the Case D simulations more closely approximated the observations in the photographs and videos, although there was still some prediction of burning too close to the perimeter, especially on the east side of the 78th, 79th, 81st and 83rd floors. The burning in the northeast corner of the 81st and 82nd floors was more intense in Case D than in Case C. The fire in the east side of the 79th floor burned more intensely and reached the south face sooner.

Nothing in the simulations explained the absence of fires in the "cold spot," the 10-window expanse toward the east of the north face of the 80th, 81st, and 82nd floors.

6.10.5 Global Heat Release Rates

Much of the information needed to simulate the fires came from laboratory-scale tests. While some of these involved enclosures several meters in dimension and fires that reached heat release rates of 10 MW and 12 GJ in total heat output, they were still far smaller than the fires that burned in the WTC towers. Figure 6–38 shows the heat release rates from the FDS simulations of the WTC fires. The peak plateau heat release rates were about 2 GW for WTC 1 and 1 GW for WTC 2. Integrating the areas under these curves produced total heat outputs from the simulated fires of about 8,000 GJ from WTC 1 and 3,000 GJ from WTC 2.

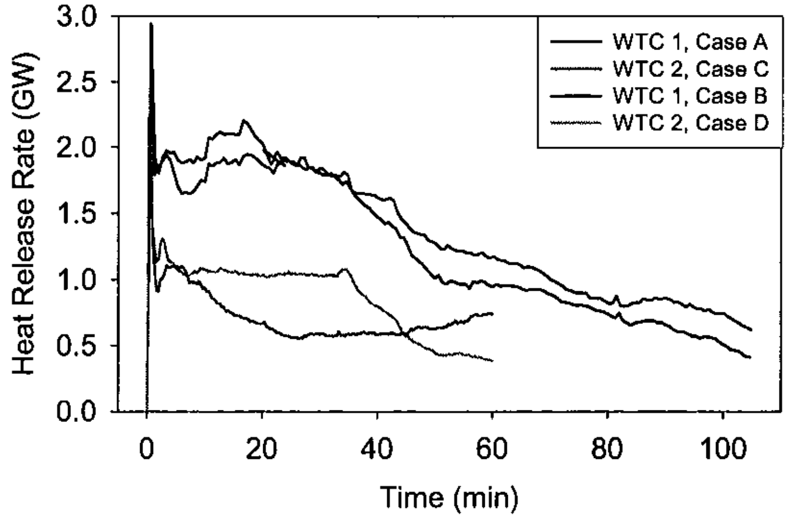


Figure 6–38. Predicted heat release rates for fires in WTC 1 and WTC 2.

6.11 DATA TRANSFER

The following data from FDS were compiled for use as boundary conditions for the finite-element calculation of the structural temperatures:

- The upper and lower layer gas temperatures, time-averaged over 100 s and spatially averaged over 3 ft. The upper layer gas temperatures were taken 1.3 ft (one grid cell) below the ceiling. The lower layer temperatures were taken 1.3 ft above the floor.
- The depth of the smoke layer.
- The absorption coefficient of the smoke layer 1.3 ft below the ceiling.

6.12 THERMAL MAPPING

6.12.1 Approach

Simulating the effect of a fire on the structural integrity of a building required a means for transferring the heat generated by the fire to the surfaces of the insulation on structural members and then conducting the heat through those members. In the Investigation, this meant mapping the time- and space-varying gas temperatures and radiation field generated by FDS onto and throughout the (insulated) columns, trusses and other elements that made up the tower structure.

This process was made difficult for these large, geometrically complex buildings by the wide disparity in length and time scales that had to be accounted for in the simulations. FDS generated thermal maps with dimensional resolution of the order of a meter and temperatures fluctuating on a time scale of milliseconds. The finite element models for thermal analysis resolved length of the order of ½ in. on a time scale of seconds. Devising a computation scheme to accommodate the finest of these scales, while simulating the largest of these scales, presented a software challenge in order to avoid unacceptably long computation times.

6.12.2 The Fire-Structure Interface

NIST developed a computational scheme to overcome this difficulty, the Fire Structure Interface (FSI).

These computations began with the structural models of each WTC tower as described in Section 6.6.4, damaged by the aircraft as described in Section 6.8.4 and exposed to fire-generated heat, as described in Section 6.10.4. For a particular tower and damage scenario, FSI "bathed" each small section of each structural member in an air environment that had been generated by FDS. For efficiency of computation, two simplifications were made:

- The fluctuating environment was averaged over 30 s intervals, and

> The transfer of radiant energy from a hot mass to a cool mass is proportional to the absolute temperature (Kelvin) to the fourth power. Thus, the contribution of the hot upper layer dominates the overall radiative heat transfer. Convective heat transfer is linearly proportional to the difference in temperature between the hot gas and the cool solid.

- The local environment was represented by a hot, soot-laden upper layer and a cooler, relatively clear lower layer.

FSI then calculated the radiative and convective heat transfer to each of these small sections using conventional physics. Finally, the temperature data were read into the ANSYS 8.0 finite element program, which applied the temperature distribution to the structural elements.

6.12.3 Thermal Insulation Properties

Equivalent Uniform Thickness of SFRM

Preliminary simulations with FSI explored the extent to which bare steel structural elements would heat more rapidly than the same elements would if they were well insulated. In one such calculation experiment, one of the largest columns in the tower structure was immersed in a furnace at 1,100 °C. Uninsulated, it took just 13 min for the steel surface temperatures to reach 600 °C, in the range where substantial loss of strength occurs. When insulated with 1 1/8 in. of SFRM, the same column had not reached that temperature in 10 hours. This established that the fires in WTC 1 and WTC 2 would not be able to significantly weaken the insulated core or perimeter columns within the 102 min and 56 min, respectively, after impact and prior to collapse. Thus, it was important to know whether the insulation was present or removed and much less important to know the exact thickness of the SFRM.

It was likely that the thinner steel bars and angles in the floor trusses would be more sensitive to the condition of the insulation. If the insulation were present, but too thin or imperfectly applied, these components might have been heated to failure in times on the order of an hour.

NIST performed additional simulations to probe the effect of gaps in the truss insulation and of variations in the thickness, similar to those observed in real SFRM application (Figure 5–6). It was evident that incorporation of these small-scale variations into the description of the structural members would have lengthened the FSI computations to an extreme. Furthermore, there was insufficient information to determine how the thickness varied over the length of the structural members. NIST combined the measured variations in the SFRM thickness (as described in Section 5.6.2) with simulations of the heat transfer through the uneven material. This led to the identification of a uniform thickness that provided the same insulation value as did the measured coatings. These values, shown in Table 5–3, were used in the thermal calculations. They were found to be greater than the specified thicknesses but slightly smaller than the average measured thicknesses, as they should be.

SFRM Thermophysical Properties

When the Investigation began, there were few published data on the insulating properties of SFRMs, especially at elevated temperatures. It was expected, and soon confirmed, that the fires could generate temperatures up to 1,100 °C. Therefore, NIST contracted for measurement of the key SFRM thermophysical properties that, along with coating thickness, determine the insulating effect of the coatings. These properties included thermal conductivity, specific heat capacity, and density. These were measured for each SFRM at temperatures up to 1,200 °C. Since there were no ASTM test methods developed specifically for characterizing the thermophysical properties of SFRMs as a function of temperature, ASTM test methods developed for other materials were used. Samples were prepared by the

manufacturers of the fire-resistive material, which included BLAZE-SHIELD DC/F and BLAZE-SHIELD II.

- The thermal conductivity measurements were performed according to ASTM C 1113, Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique). The room temperature values were in general agreement with the manufacturer's published values for both materials. The thermal conductivities increased with temperature.

- Specific heat capacity was measured in accordance with ASTM E 1269, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry (DSC). By including DSC measurement of a NIST Reference Material (sapphire), the measured SFRM quantities were directly traceable to NIST standards.

- The densities of the SFRMs were calculated from measurements of changes in the mass and dimensions of samples as their temperatures were increased. The length-change measurements were performed according to ASTM E 228, Standard Test Method for Linear Thermal Expansion of Solid Materials. The mass loss measurements were performed according to ASTM E 1131, Standard Test Method for Compositional Analysis by Thermogravimetry.

It was not known which type(s) of gypsum wallboard were used to enclose the core columns. Therefore, the thermophysical properties of four types of gypsum panels were examined.

- Thermal conductivity was measured using the heated probe technique described in ASTM D 5334, Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure. In general, the thermal conductivity initially decreased as the temperature increased to 200 °C and then increased with increasing temperature above 300 °C.

- Specific heat capacities of the cores of the four gypsum panel samples were measured using a differential scanning calorimeter at NIST according to ASTM E 1269, Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry. The four panels had nearly identical specific heat capacities as a function of temperature.

- The variation of density with temperature was determined from the change in volume of the gypsum material and the mass loss. The linear expansion was determined using a dilatometer and the mass loss from thermogravimetric analysis. All four materials showed the same trend as a function of temperature.

6.12.4 FSI Uncertainty Assessment

As was done for FDS, it was necessary to establish the quality of FSI's predictions of temperature profiles within insulated and bare structural steel components. This was accomplished using data from a series of six tests in which assorted steel members were exposed to controlled fires of varying heat release rate and radiative intensity. The steel members, depicted in Figures 6–39 through 6–41, were either bare or coated with sprayed BLAZE-SHIELD DC/F in two thicknesses. The fibrous insulation was applied by an

experienced applicator, who took considerable care to apply an even coating of the specified thickness. As such, the insulated test subjects represent a best case in terms of thickness and uniformity. Figure 6–42 shows some of the coated components.

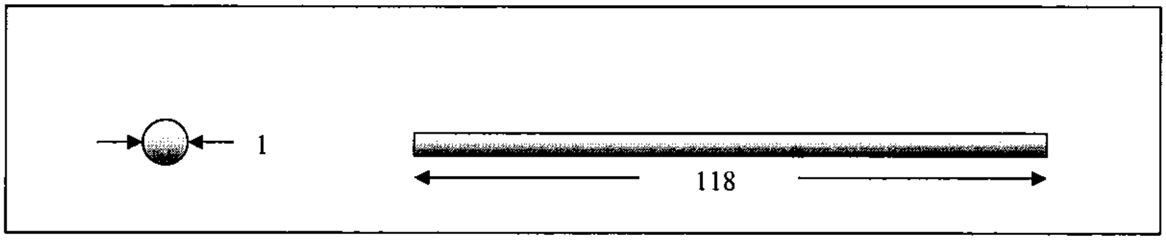


Figure 6–39. Simple bar dimensions (in.).

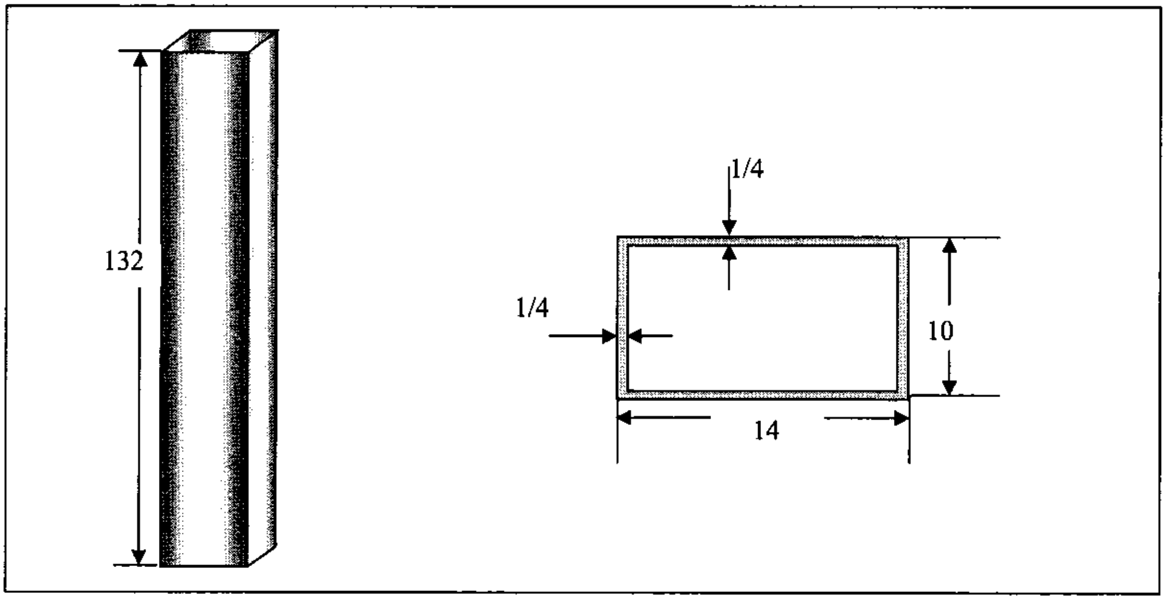


Figure 6–40. Tubular column dimensions (in.).

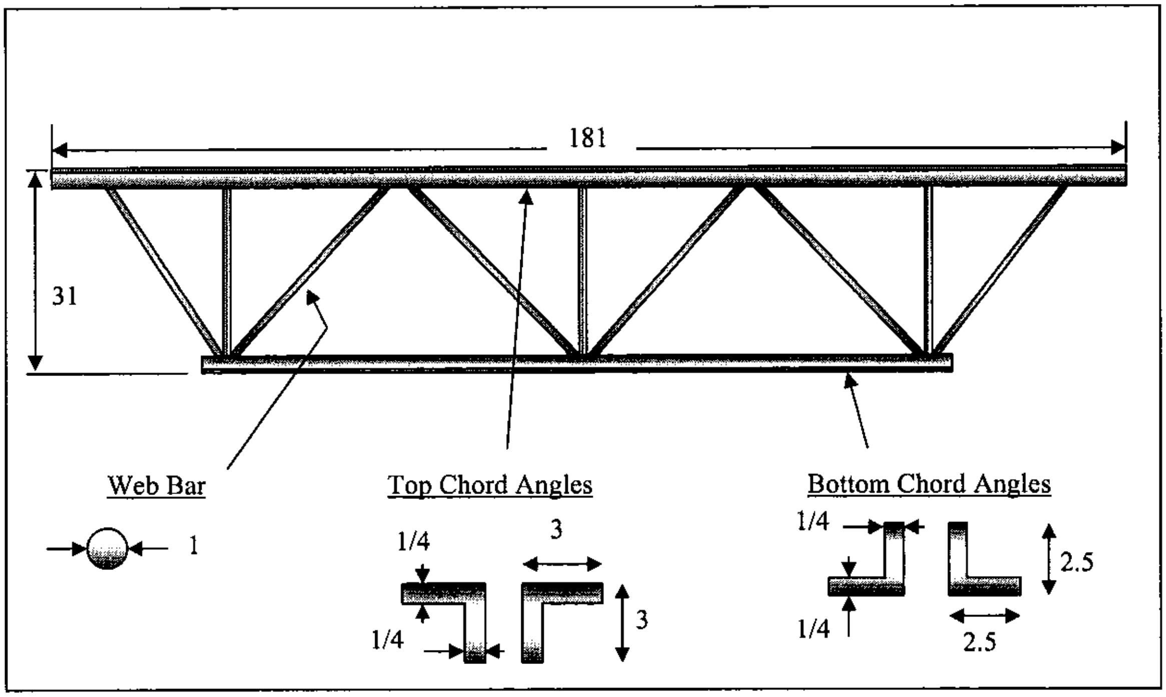


Figure 6–41. Truss Dimensions (in.).

Source: NIST.

Figure 6–42. SFRM-coated steel components prior to a test.

Table 6–7 shows the dimensions and variability of the insulation for the two successful tests involving coated steel. The thickness measurements were taken at numerous locations along the perimeter and length of each specimen using a pin thickness gauge specifically designed for this type of insulation.

Table 6–7. Summary of insulation on steel components.

Test	Item	Specified Thickness (in.)	Applied Thickness (in.)	
			Mean	Std. Deviation
5	Bar	0.75	0.91	0.22
	Column	1.50	1.61	0.12
	Truss A	0.75	1.06	0.28
	Truss B	1.50	1.59	0.32
6	Bar	0.75	1.00	0.18
	Column	0.75	0.84	0.14
	Truss A	0.75	1.02	0.27
	Truss B	0.75	1.01	0.27

Temperatures were recorded at multiple locations on the surfaces of the steel, the insulation, and the compartment. As an example, Figure 6–43 shows the finite element representation of the coated truss.

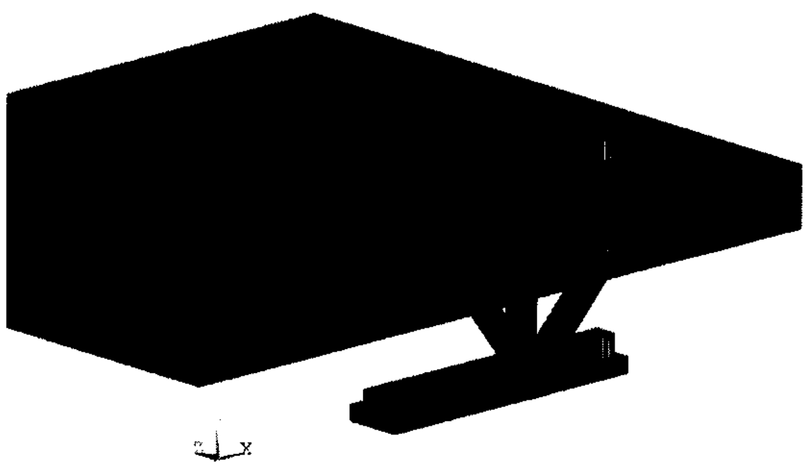


Figure 6–43. Finite element representation of the insulated steel truss (blue), the SFRM (violet), and the ceiling (red).

Figure 6–44 compares the measured and predicted temperatures on the steel surface of the top chord of a bare truss. Figure 6–45 is the analogous plot of the measured and predicted temperatures on the steel surface of the top chord of a truss insulated with 3/4 in. of BLAZE-SHIELD DC/F. Similar curves were generated for each of the steel pieces, bare and insulated.

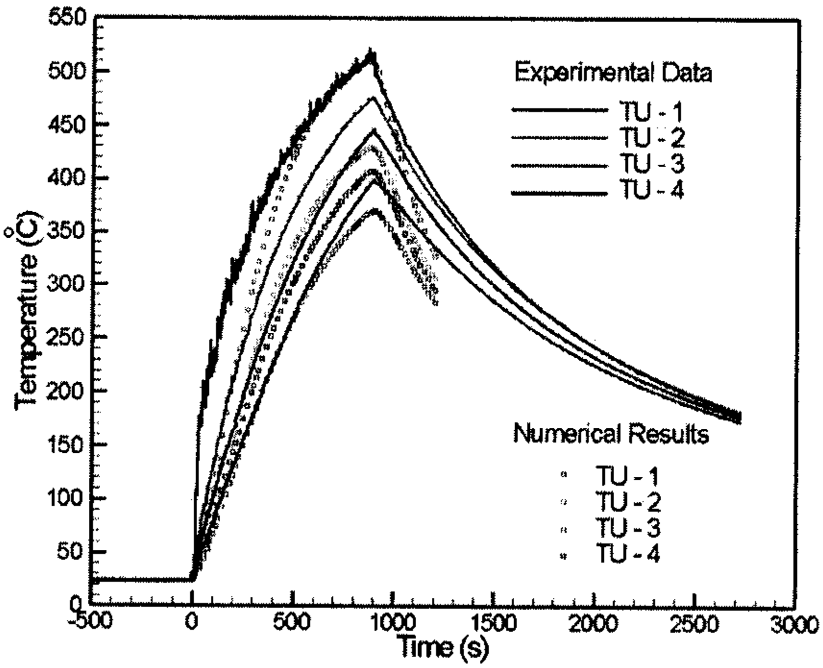


Figure 6–44. Comparison of numerical simulations with measurements for the steel surface temperature at four locations on the top chord of a bare truss.

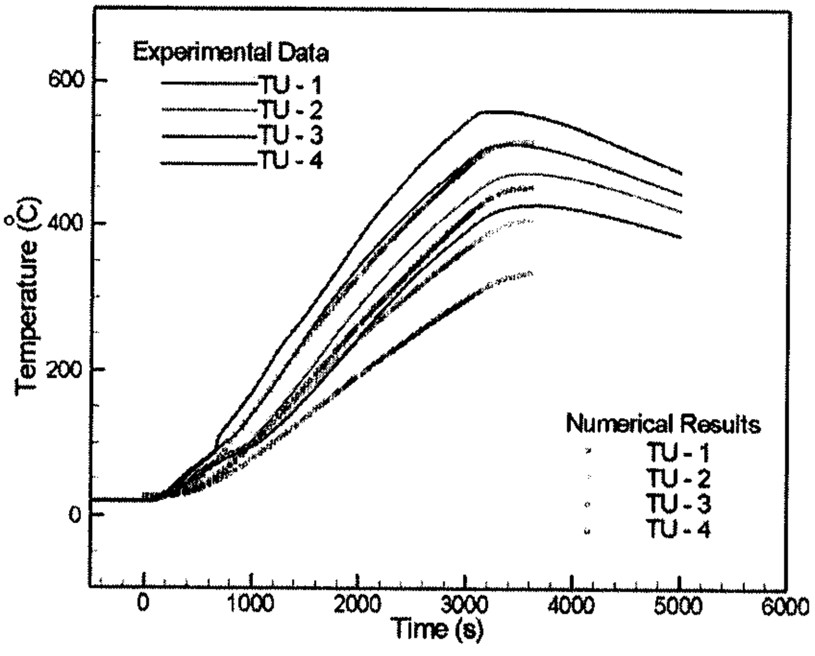


Figure 6–45. Comparison of numerical simulations with measurements for the temperature of the steel surface at four locations on the top chord of an insulated truss.

Examination of the graphs for the insulated steel pieces indicated the following:

- FSI captured the shape of the temperature rise at the steel surfaces and the significant decrease in the rate of temperature rise when the SFRM was present.
- The times to the peak temperature (or a near-plateau) were predicted to within about a minute in all cases.
- There was no consistent pattern of overprediction or underprediction of the surface temperatures.
- On the average, the numerical predictions of the steel surface temperature were within 7 percent of the experimental measurements for bare steel elements and within 17 percent for the insulated steel elements. The former was within the combined uncertainty in the temperature measurements and the heat release rate in the fire model. The increase in the latter was attributed to model sensitivity to the SFRM coating thickness and thermal conductivity.

In general, the FSI added little to the overall uncertainty in the simulation of the temperatures at the outer surfaces of bare steel elements and, more importantly, at the SFRM-steel interface.

An additional, important outcome of the experiments was the demonstration of the insulating effect of even 3/4 in. of SFRM. Trusses, made of relatively thin steel, were far more susceptible to heating than the perimeter and core columns. As shown in Figure 2–10, in 15 min, a bare truss reached a temperature at which significant loss of strength was imminent. An identical, but insulated truss had not reached that temperature in 50 min.

6.12.5 The Four Cases

FSI imposed the thermal environment from each of the four FDS fire scenarios (Cases A and B for WTC 1 and Cases C and D for WTC 2) on the four damaged structures from the aircraft simulations, which carried the same case letters. The FSI output files carried the same case letters as the input files.

The FSI calculations were performed at time steps ranging from 1 ms to 50 ms. Use of the resulting data set for structural analysis would have required a prohibitive amount of computation time. Thus, for each case, the instantaneous temperature and temperature gradient for each grid volume was provided at 10 min intervals after aircraft impact. For WTC 1, there were 10 such intervals, ending at 6,000 s; for WTC 2 there were 6 intervals, ending at 3,600 s. Comparison of these coarsely timed output files with files at 1 min resolution showed any differences to be within the combined uncertainty.

Each floor in the FSI simulation provided thermal information for the floor assembly above. Thus, there was not sufficient information for FSI to model the lowest floor in the FDS simulations. For WTC 1, the global thermal response generated by FSI included floors 93 through 99; for WTC 2, the included floors were 79 through 83.

For ease of visualization, two graphic representations were developed. Figure 6–46 shows an example of the temperature map for the 96th floor of WTC 1. Severed columns and broken floor segments are not shown. Figure 6–47 shows a similar map for the 81st floor of WTC 2.

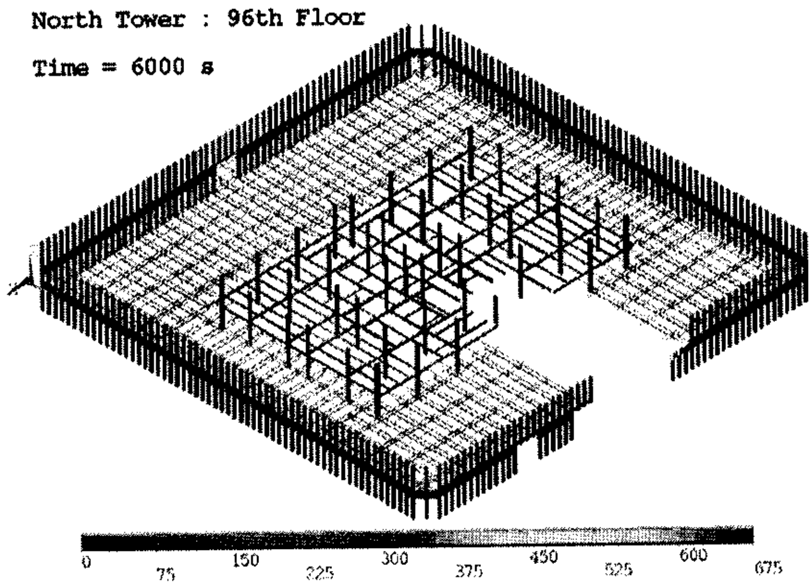


Figure 6–46. Temperatures (°C) on the columns and trusses of the 96th floor of WTC 1 at 6,000 s after aircraft impact, Case B.

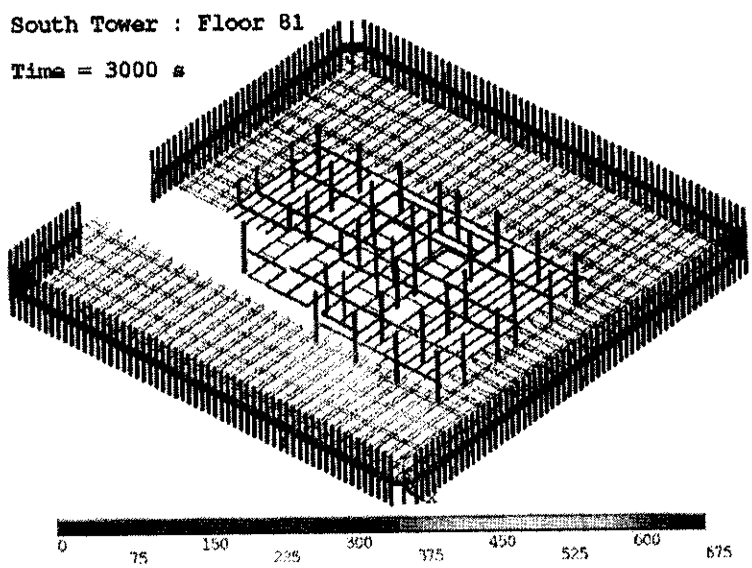


Figure 6–47. Temperatures (°C) on the columns and trusses of the 81st floor of WTC 2 at 3,000 s after aircraft impact, Case D.

A third visualization tool was animation of the evolving temperatures of the columns. Frames from an example, again of the 96th floor of WTC 1, Case A, are shown in Figure 6–48. The size of the square representing a column represents its yield strength. Columns may have been heated when the fire was nearby and then cooled after the local combustibles were consumed.

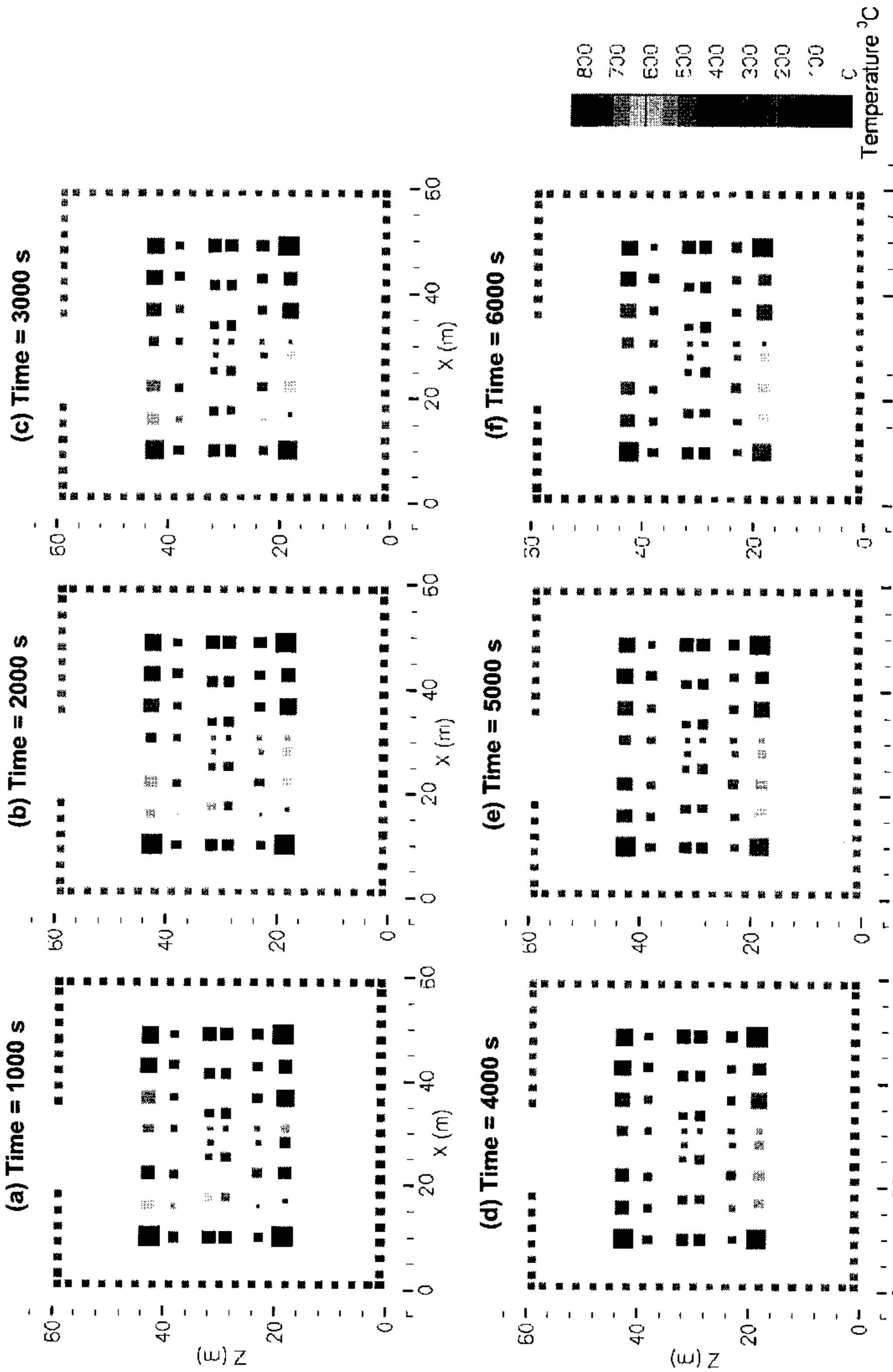


Figure 6–48. Frames from animation of the thermal response of columns on the 96th floor of WTC 1, Case A.

6.12.6 Characterization of the Thermal Profiles

Tables 6–8 and 6–9 summarize the regions of the floors in which the structural steel reached temperatures at which their yield strengths would have been significantly diminished. Instances of brief heating of one or two columns early in the fires were not included.

Even in the vicinity of the fires, the columns and trusses for which the insulation was intact did not heat to temperatures where significant loss of strength occurred.

Unlike the simulations of the aircraft impact and the fires, there was no evidence, photographic or other, for direct comparison with the FSI results.

Table 6–8. Regions in WTC 1 in which temperatures of structural steel exceeded 600 °C.

Floor Number	Trusses		Perimeter Columns		Core Columns	
	Case A	Case B	Case A	Case B	Case A	Case B
93	–	–	–	–	–	–
94	–	–	–	–	N, S	NE, S
95	N	N, S	–	–	S	NW, S
96	N	N, S	–	S	S	W, S
97	N, S	N, S	–	S	N	W, S
98	N	N, S	–	–	–	–
99	–	–	–	–	–	–

Key: N, north; NE, northeast; NW, northwest; S, south; W, west.

Table 6–9. Regions in WTC 2 in which temperatures of structural steel exceeded 600 °C.

Floor Number	Trusses		Perimeter Columns		Core Columns	
	Case C	Case D	Case C	Case D	Case C	Case D
79	–	–	–	–	–	–
80	–	–	–	–	–	–
81	NE	NE	NE	NE	–	NE
82	E	E	E	E	E	E
83	E	E	–	E	–	E

Key: E, east; NE, northeast.

6.13 MEASUREMENT OF THE FIRE RESISTANCE OF THE FLOOR SYSTEM

As described in Section 5.4.7, the composite floor system, composed of open-web, lightweight steel trusses topped with a slab of lightweight concrete, was an innovative feature. As further noted in Section 5.6.2, the approach to achieving the specified fire resistance for these floors was the use of a SFRM. Documents indicated that the fire performance of the composite floor system of the WTC towers was an issue of concern to the building owners and designers. However, NIST found no evidence regarding the technical basis for the selection of insulation material for the floor trusses or for the insulation thickness to achieve a 2 hour rating. Further, NIST has found no evidence that fire resistance tests of the WTC floor system were conducted.

Most of the possible building collapse sequences included some contribution from the floors, ranging from their ability to transfer load to their initiating the collapse by their failure. Thus, it became central to the Investigation to obtain data regarding the limits of the insulated floors in withstanding the heat from the fires. The standard test for determining the fire endurance of floor assemblies is ASTM E 119, "Standard Test Methods for Fire Tests of Building Construction and Materials." The conduct of the test is described in Section 1.2.2 under "Fire Protection Systems."

Accordingly, NIST contracted with Underwriters Laboratories, Inc. to conduct tests to obtain information on the fire endurance of trusses like those in the WTC towers. The objective was to understand the effects of three factors:

- Scale of the test. There were no established facilities capable of testing the 60 ft lengths of the long spans that were used in the towers, but there is a history of testing reduced-scale assemblies and scaling them to practical dimensions. In the Investigation's tests, the full-scale test specimens were 35 ft long, equal to the shorter span between the core and the perimeter of the WTC towers. Their construction replicated, as closely as possible, the original short-span floors. The reduced-scale specimens were half that length and height. All assemblies were 14 ft wide. The simulation of a "maximum load condition," as required by ASTM E 119, involved placing a combination of concrete blocks and containers filled with water on the top surface of the floor. The load on the shorter truss was double that of the longer truss to achieve the same state of stress in both trusses. Traditionally, relatively small-scale assemblies have been tested and results have been scaled to practical floor system spans.

- SFRM thickness. The Port Authority originally specified BLAZE-SHIELD D as the SFRM, applied to a ½ in. covering. The average measured thicknesses were found to be approximately 0.75 in. These two thicknesses of BLAZE-SHIELD D were used in the Investigation tests.

- Test restraint conditions. In 1971, well after the design of the towers was completed, the ASTM E 119 Standard began differentiating between thermally restrained and unrestrained floor assemblies. An unrestrained assembly is free to expand thermally and to rotate at its supports; a restrained assembly is not. It is customary in the United States to conduct standard fire tests of floor assemblies in the restrained condition. The current standard describes a means to establish unrestrained ratings for floor assemblies from restrained test results. In practice, a floor assembly such as that used in the WTC towers is neither restrained nor unrestrained but is likely somewhere in between. Testing under both restraint conditions, then, is thought to bound performance under the standard fire exposure. In addition, it provided a comparison of unrestrained ratings developed from both restrained and unrestrained test conditions.

The test plan included four tests, which varied the three factors:

Test 1: 35 ft floor, ¾ in. insulation, restrained

Test 2: 35 ft floor, ¾ in. insulation, unrestrained

Test 3: 17 ft floor, ¾ in. insulation, restrained

Test 4: 17 ft floor, ½ in. insulation, restrained

The results of the four tests are summarized as follows:

- All four test assemblies were able to withstand standard fire conditions for between ¾ hour and 2 hours without exceeding the limits prescribed by ASTM E 119.
- All four test specimens sustained the maximum design load for approximately 2 hours without collapsing.
- The restrained full-scale floor system obtained a fire resistance rating of 1½ hours, while the unrestrained floor system achieved a 2 hour rating. Past experience with the ASTM E 119 test method led investigators to expect the unrestrained floor assembly to receive a lower rating than the restrained assembly.
- For assemblies with a ¾ in. SFRM thickness, the 17 ft assembly's fire rating was 2 hours; the 35 ft assembly's rating was 1½ hours. This result raised the question of whether or not a fire rating of a 17 ft floor assembly is scalable to the longer spans in the WTC towers.
- The specimen in Test 4, with a fire rating of ¾ hour, would not have met the 2 hour requirement of the NYC Building Code.

The Investigation Team was cautious about using these results directly in the formulation of collapse hypotheses. In addition to the scaling issues raised by the test results, the fires in the towers on September 11, and the resulting exposure of the floor systems, were substantially different from the conditions in the test furnaces. Nonetheless, the results established that this type of assembly was capable of sustaining a large gravity load, without collapsing, for a substantial period of time relative to the duration of the fires in any given location on September 11.

6.14 COLLAPSE ANALYSIS OF THE TOWERS

6.14.1 Approach to Determining the Probable Collapse Sequences

At the core of NIST's reconstruction of the events of September 11, 2001, were the archive of photographic and video evidence, the observations of people who were on the scene, the assembled documents describing the towers and the aircraft, and Investigation-generated experimental data on the properties of construction and furnishing materials and the behavior of the fires. Information from all of these sources fed the computer simulations of the towers, the aircraft impacts, the ensuing fires and their heating of the structural elements, and the structural changes that led to the collapse of the towers. To the extent that the input information was complete and accurate, the output of the simulations would have provided definitive responses to the first three objectives of the Investigation. However, the available information, as extensive as it was, was neither complete nor of assured precision. As a result, the Investigation Team took steps to ensure that the conclusions of the effort were credible explanations for how the buildings collapsed and the extent to which the casualties occurred.

One principal step was the determination of those variables that most affected the outcome of the various computer simulations. Sensitivity studies and examination of components and subsystems were carried out for the modeling of the aircraft impact, the fires, and the structural response to impact damage and fires. For each of the most influential variables, a central or middle value and reasonable high and low values were identified. Further computations refined the selection of these values. The computations also were improved to include physical processes that could play a significant role in the structural degradation of the towers.

The Investigation Team then defined three cases for each building by combining the middle, less severe, and more severe values of the influential variables. Upon a preliminary examination of the middle cases, it became clear that the towers would likely remain standing. The less severe cases were discarded after the aircraft impact results were compared to observed events. The middle cases (which became Case A for WTC 1 and Case C for WTC 2) were discarded after the structural response analysis of major subsystems were compared to observed events. The more severe case (which became Case B for WTC 1 and Case D for WTC 2) was used for the global analysis of each tower.

Complete sets of simulations were then performed for Cases B and D. To the extent that the simulations deviated from the photographic evidence or eyewitness reports, the investigators adjusted the input, but only within the range of physical reality. Thus, for instance, the observed window breakage was an input to the fire simulations and the pulling forces on the perimeter columns by the sagging floors were adjusted within the range of values derived from the subsystem computations.

The results were a simulation of the structural deterioration of each tower from the time of aircraft impact to the time at which the building became unstable, i.e., was poised for collapse. Cases B and D accomplished this in a manner that was consistent with the principal observables and the governing physics.

6.14.2 Results of Global Analysis of WTC 1

After the aircraft impact, gravity loads that were previously carried by severed columns were redistributed to other columns. The north wall lost about 7 percent of its loads after impact. Most of the load was transferred by the hat truss, and the rest was redistributed to the adjacent exterior walls by spandrels. Due to the impact damage and the tilting of the building to the north after impact, the south wall also lost gravity load, and about 7 percent was transferred by the hat truss. As a result, the east and west walls and the core gained the redistributed loads through the hat truss.

Structural steel and concrete expand when heated. In the early stages of the fire, temperatures of structural members in the core rose, and the resulting thermal expansion of the core columns was greater than the thermal expansion of the (cooler) exterior walls. The floors also thermally expanded in the early stages of the fires. About 20 min after the aircraft impact, the difference in the thermal expansion between the core and exterior walls, which was resisted by the hat truss, caused the core columns' loads to increase. As floor temperatures increased, the floors sagged and began to pull inward on the exterior wall. As the fires continued to heat areas of the core that were without insulation, the columns weakened and shortened and began to transfer their loads to the exterior walls through the hat truss until the south wall started to bow inward due to the inward pull of the sagging floors. At about 100 min, approximately 20 percent of the core loads had been transferred by the hat truss to the exterior walls due to weakening of

the core, the loads on the north and south walls had each increased by about 10 percent, and those on the east and west walls had about a 25 percent increase. The increased loads on the east and west walls were due to their relatively higher stiffness compared to the impact damaged north wall and bowed south walls.

The inward bowing of the south wall caused failure of exterior column splices and spandrels, and these columns became unstable. The instability spread horizontally across the entire south face. The south wall, now unable to bear its gravity loads, redistributed these loads to the thermally weakened core through the hat truss and to the east and west walls through the spandrels. The building section above the impact zone began tilting to the south as the columns on the east and west walls rapidly became unable to carry the increased loads. This further increased the gravity loads on the core columns. The gravity loads could no longer be redistributed, nor could the remaining core and perimeter columns support the gravity loads from the floors above. Once the upper building section began to move downwards, the weakened structure in the impact and fire zone was not able to absorb the tremendous energy of the falling building section and global collapse ensued.

6.14.3 Results of Global Analysis of WTC 2

Before aircraft impact, the load distribution across the exterior walls and core was symmetric with respect to the centerline of each exterior wall. After aircraft impact, the exterior column loads on the south side of the east and west walls and on the east side of south wall increased. This was due to the leaning of the building core towards the southeast. After aircraft impact, the core carried 6 percent less load. The north wall load reduced by 6 percent and the east face load increased by 24 percent. The south and west walls carried 2 percent to 3 percent more load.

In contrast to the fires in WTC 1, which generally progressed from the north side of the building to the south side over approximately 1 hour, the fires in WTC 2 were located on the east side of the core and floors from the time of impact until the building collapsed, with the fires spreading somewhat from south to north. With insulation dislodged over much of the same area, the structural temperatures became elevated in the core, floors, and exterior walls at similar times. During the early stages of the fires, columns with dislodged insulation elongated due to thermal expansion. As the structural temperatures continued to rise, the columns thermally weakened and consequently shortened. Thermal expansion of the floors also occurred early in the fires, but as floor temperatures increased, the floors sagged and began to pull inward on the exterior columns.

The south exterior wall displaced downward following the aircraft impact, but did not displace further until the east wall became unstable 43 min later. The inward bowing of the east wall, due to the inward pull of the sagging floors, caused failure of exterior column splices and spandrels and resulted in the east wall columns becoming unstable. The instability progressed horizontally across the entire east face. The east wall, now unable to bear its gravity loads, redistributed them to the thermally weakened core through the hat truss and to the east and west walls through the spandrels.

The building section above the impact zone began tilting to the east and south as column instability progressed rapidly from the east wall along the adjacent north and south walls, and increased the gravity load on the weakened east core columns. The gravity loads could no longer be redistributed, nor could the remaining core and perimeter columns support the gravity loads from the floors above. As with WTC 1, once the upper building section began to move downwards, the weakened structure in the impact

and fire zone was not able to absorb the tremendous energy of the falling building section and global collapse ensued.

6.14.4 Events Following Collapse Initiation

Failure of the south wall in WTC 1 and east wall in WTC 2 caused the portion of the building above to tilt in the direction of the failed wall. The tilting was accompanied by a downward movement. The story immediately below the stories in which the columns failed was not able to arrest this initial movement as evidenced by videos from several vantage points.

The structure below the level of collapse initiation offered minimal resistance to the falling building mass at and above the impact zone. The potential energy released by the downward movement of the large building mass far exceeded the capacity of the intact structure below to absorb that through energy of deformation.

Since the stories below the level of collapse initiation provided little resistance to the tremendous energy released by the falling building mass, the building section above came down essentially in free fall, as seen in videos. As the stories below sequentially failed, the falling mass increased, further increasing the demand on the floors below, which were unable to arrest the moving mass.

The falling mass of the building compressed the air ahead of it, much like the action of a piston, forcing material, such as smoke and debris, out the windows as seen in several videos.

NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photographs and videos from several angles clearly show that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

6.14.5 Structural Response of the WTC Towers to Fire without Impact or Thermal Insulation Damage

To complete the assessment of the relative roles of aircraft impact and ensuing fires, NIST examined whether an intense, but conventional, fire, occurring without the aircraft impact, could have led to the collapse of a WTC tower, were the tower in the same condition as it was on September 10, 2001. NIST used the observations, information, and analyses developed during the Investigation to enable the formulation of probable limits to the damage from such a fire. Since a complete analysis beyond the actual collapse times of the towers was not conducted, the findings in this section represent NIST's best technical judgment based on the available observations, information, and analyses:

- Ignition on a single floor by a small bomb or other explosion. If arson were involved, there might have been multiple small fires ignited on a few floors.
- Air supply determined by the building ventilation system.
- Moderate fire growth rate. In the case of arson, several gallons of an accelerant might have been applied to the building combustibles, igniting the equivalent of several workstations.

- Water supply to the sprinklers and standpipes maliciously compromised.
- Intact structural insulation and interior walls.

The four cases described in this chapter represented fires that were far more severe than this:

- About 10,000 gallons of jet fuel were sprayed into multiple stories, quickly and simultaneously igniting hundreds of workstations and other combustibles.
- The aircraft and subsequent fireballs created large open areas in the building exterior through which air could flow to support the fires.
- The impact and debris removed the insulation from a large number of structural elements that were then subjected to the heat from the fires.

Additional findings from the Investigation showed that:

- Both the results of the multiple workstation experiments and the simulations of the WTC fires showed that the combustibles in a given location, if undisturbed by the aircraft impact, would have been almost fully burned out in about 20 min.
- In the simulations of Cases A through D, none of the columns and trusses for which thermal insulation was intact reached temperatures at which significant loss of strength occurred. Thermal analyses showed that steel temperatures in areas where the insulation remained intact rarely exceeded 400 °C in WTC 1 and 500 °C in WTC 2.
- In WTC 1, if fires had been allowed to continue past the time of building collapse, complete burnout would likely have occurred within a short time since the fires had already traversed around the entire floor and most of the combustibles would already have been consumed (see Figure 6–38). During the extended period from collapse to burnout, the steel temperatures would likely not have increased very much. The installed insulation in the fire-affected floors of this building had been upgraded to an average thickness of 2.5 in.
- In a fire simulation of WTC 2, that was extended for 2 hours beyond Case D and with all windows broken during this period, the temperatures in the truss steel on the west side of the building (where the insulation was undamaged) increased for about 40 min before falling off rapidly as the combustibles were consumed. Results for a typical floor (floor 81) showed that temperatures of 700 °C to 760 °C were reached over approximately 15 percent of the west floor area for less than 10 min. Approximately 60 percent of the floor steel had temperatures between 600 °C and 700 °C for about 15 min. Approximately 70 percent of the floor steel had temperatures that exceeded 500 °C for about 45 min. At these temperatures, the floors would be expected to sag and then recover a portion of the sag as the steel began to cool. Based on results for Cases C and D, the temperatures of the insulated exterior and core columns would not have increased to the point where significant loss of strength or stiffness would occur during these additional 2 hours. With intact, cool core columns, any inward bowing of the west exterior wall that might occur would be readily supported by the adjacent exterior walls and core columns.

- Both WTC 1 and WTC 2 were stable after the aircraft impact, standing for 102 min and 56 min, respectively. The global analyses with structural impact damage showed that both towers had considerable reserve capacity. This was confirmed by analysis of the post-impact vibration of WTC 2, the more severely damaged building, where the damaged tower oscillated with a peak amplitude that was between 30 percent and 40 percent of the sway under hurricane force winds for which the towers were designed and at periods nearly equal to the first two translation and torsion mode periods calculated for the undamaged structure.

- Computer simulations, supported by the results of large-scale fire tests and furnace testing of floor subsystems, showed that insulated structural steel, when coated with the average installed insulation thickness of ¾ in., would not have reached high temperatures (i.e., greater than 650 °C) from nearby fires for a longer time than the burnout time of the combustibles (approximately 20 min for 4 lb/ft^2 of combusted material). Simulations also showed that variations in thickness resulting from normal application, even with occasional gaps in coverage, would not have changed this result.

- Inward bowing of the exterior walls in both WTC 1 and WTC 2 was observed only on the face with the long-span floor system. In WTC 1, this was found to be the case even though equally extensive fires were observed on all faces. In WTC 2, fires were not observed on the long-span west face and were less intense on the short-span faces than on the east face.

- Inward bowing was a necessary but not sufficient condition to initiate collapse. In both WTC 1 and WTC 2, significant weakening of the core due to aircraft impact damage and thermal effects was also necessary to initiate building collapse.

- The tower structures had significant capacity to redistribute loads (a) from bowed walls to adjacent exterior walls with short-span floors via the arch action of spandrels, and (b) between the core and exterior walls via the hat truss and, to a lesser extent, the floors.

In evaluating how the undamaged towers would have performed in an intense, conventional fire, NIST considered the following factors individually and in combination:

- The *temperatures* that would be reached in structural steel components with intact insulation.

- The *extent of the area* over which high temperatures (e.g., greater than 600 °C where significant thermal weakening of the steel occurs) would be reached at any given time.

- The *duration* over which the high temperatures would be sustained concurrently in any given area.

- The *length of the floor span* (long or short) where high temperatures would be reached.

- The *number of floors* with areas where high temperatures would be sustained concurrently in the long-span direction.

- The *potential for inward bowing of exterior walls* (i.e., magnitude and extent of bowing over the width of the face and the number of floors involved) due to thermally induced floor sagging of long-span floors and associated inward pull forces.

- The *capacity of the structure to redistribute loads* (e.g., via the spandrels, hat truss, and floors) if the thermal conditions were sufficiently intense to cause inward bowing of the exterior walls.

In addition, NIST considered the following known facts:

- WTC 1 did not collapse during the major fire in 1975, which engulfed a large area (about one-fourth of the floor area or 9,000 ft^2) on the southeast quadrant of the 11th floor. At the time, office spaces in the towers were not sprinklered. The fire caused minimal damage to the floor system with the ½ in. specified insulation thickness applied on the trusses (four trusses were slightly distorted), and at no time was the load-carrying capacity compromised for the floor system or the structure as a whole.

- Four standard fire resistance tests of floor assemblies like those in the WTC towers conducted as part of this Investigation showed that (a) it took about 90 min of sustained heating in the furnace for temperatures to exceed 600 °C on steel truss members with either ½ in. or ¾ in. insulation thickness, and (b) in no case was the load-carrying capacity compromised by heating of the floor system for 2 hours at furnace temperatures, with applied loads exceeding those on September 11 by a factor of two.

From these findings, factors, and observed performance, NIST concluded:

- In the absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001, likely would not have led to the collapse of a WTC tower.

- The condition of the insulation prior to aircraft impact, which was found to be mostly intact, and the insulation thickness on the WTC floor system contributed to, but did not play a governing role, in initiating collapse of the towers.

- The towers likely would not have collapsed under the combined effects of aircraft impact and the subsequent multi-floor fires encountered on September 11 if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

These findings apply to fires that are substantially similar to or less intense than those encountered on September 11, 2001. They do not apply to a standard fire or an assumed fire exposure which has (a) uniform high temperatures over an entire floor or most of a floor (note that the WTC floors were extremely large) and concurrently over multiple floors, (b) high temperatures that are sustained indefinitely or for long periods of time (greater than about 20 min at any location), and (c) combusted fire loads that are significantly greater than those considered in the analyses. They also do not apply if the capacity of the undamaged structure to redistribute loads via the spandrels, hat truss, and floors is not accounted for adequately in a full 3-dimensional simulation model of the structure.

6.14.6 Probable WTC 1 Collapse Sequence

Aircraft Impact Damage

- The aircraft impact severed a number of exterior columns on the north wall from the 93rd to the 98th floors, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the north side of the core. Core columns were also damaged toward the center of the core. Insulation was damaged from the impact area to the south perimeter wall, primarily through the middle one-third to one-half of the core width. Finally, the aircraft debris removed a single exterior panel at the center of the south wall between the 94th and 96th floors.
- The impact damage to the exterior walls and to the core resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The hat truss resisted the downward movement of the north wall.
- Loads on the damaged core columns were redistributed mostly to adjacent intact core columns and to a lesser extent to the north perimeter columns through the core floor systems and the hat truss.
- As a result of the aircraft impact damage, the north and south walls each carried about 7 percent less gravity load after impact, and the east and west walls each carried about 7 percent more load. The core carried about 1 percent more gravity load after impact.

Thermal Weakening of the Structure

- Under the high temperatures and stresses in the core area, the remaining core columns with damaged insulation were thermally weakened and shortened, causing the columns on the floors above to move downward. The hat truss resisted the core column shortening and redistributed loads to the perimeter walls. The north and south walls' loads increased by about 10 percent, and the east and west walls' loads increased by about 25 percent, while the core's loads decreased by about 20 percent.
- The long-span sections of the 95th to 99th floors on the south side weakened with increasing temperatures and began to sag. Early on, the floors on the north side had sagged and then contracted as the fires moved to the south and the floors cooled. As the fires intensified on the south side, the floors there sagged, and the floor connections weakened. About 20 percent of the connections on the south side of the 97th and 98th floors failed.
- The sagging floors with intact floor connections pulled inward on the south perimeter columns, causing them to bow inward.

Collapse Initiation

- The bowed south wall columns buckled and were unable to carry the gravity loads. Those loads shifted to the adjacent columns via the spandrels, but those columns quickly became overloaded as well. In rapid sequence, this instability spread all the way to the east and west walls.
- The section of the building above the impact zone (near the 98th floor), acting as a rigid block, tilted at least 8 degrees to the south.
- The downward movement of this structural block was more than the damaged structure could resist, and global collapse began.

6.14.7 Probable WTC 2 Collapse Sequence

Aircraft Impact Damage

- The aircraft impact severed a number of exterior columns on the south wall from the 78th floor to the 84th floor, and the wall section above the impact zone moved downward.
- After breaching the building's perimeter, the aircraft continued to penetrate into the building, severing floor framing and core columns at the southeast corner of the core. Insulation was damaged from the impact area through the east half of the core to the north and east perimeter walls. The floor truss seat connections over about one-fourth to one-half of the east side of the core were severed on the 80th and 81st floors and over about one-third of the east perimeter wall on the 83rd floor. The debris severed four columns near the east corner of the north wall between the 80th and 82nd floors.
- The impact damage to the perimeter walls and to the core resulted in redistribution of severed column loads, mostly to the columns adjacent to the impact zones. The impact damage to the core columns resulted in redistribution of severed column loads, mainly to other intact core columns and the east exterior wall. The hat truss resisted the downward movement of the south wall.
- As a result of the aircraft impact damage, the core carried about 6 percent less gravity load. The north wall carried about 10 percent less, the east face carried about 24 percent more, and the west and south faces carried about 3 percent and two percent more, respectively.
- The core was then leaning slightly toward the south and east perimeter walls. The perimeter walls restrained the tendency of the core to lean via the hat truss and the intact floors.

Thermal Weakening of the Structure

- Under the high temperatures and stresses in the core area, the remaining core columns with damaged insulation were thermally weakened and shortened, causing the columns on the floors above to move downward.

- At this point, the east wall carried about 5 percent more of the gravity loads, and the core carried about 2 percent less. The other three walls carried between 0 percent and 3 percent less.

- The long-span floors on the east side of the 79th to 83rd floors weakened with increasing temperatures and began to sag. About one-third of the remaining floor connections to the east perimeter wall on the 83rd floor failed.

- Those sagging floors whose seats were still intact pulled inward on the east perimeter columns, causing them to bow inward. The inward bowing increased with time.

Collapse Initiation

- As in WTC 1, the bowed columns buckled and became unable to carry the gravity loads. Those loads shifted to the adjacent columns via the spandrels, but those columns quickly became overloaded. In rapid sequence, this instability spread all across the east wall.

- Loads were transferred from the failing east wall to the weakened core through the hat truss and to the north and south walls through the spandrels. The instability of the east face spread rapidly along the north and south walls.

- The building section above the impact zone (near the 82nd floor) tilted 7 degrees to 8 degrees to the east and 3 degrees to 4 degrees to the south prior to significant downward movement of the upper building section. The tilt to the south did not increase any further as the upper building section began to fall, but the tilt to the east was seen to increase to 20 degrees until dust clouds obscured the view.

- The downward movement of this structural block was more than the damaged structure could resist, and the global collapse began.

6.14.8 Accuracy of the Probable Collapse Sequences

Independent assessment of the validity of the key steps in the collapse of the towers was a challenging task. Some of the photographic information had been used to direct the simulations. For example, the timing of the appearance of broken windows was an input to the fire growth modeling. However, there were significant observables that were usable as corroborating evidence, as shown in Tables 6–10 and 6–11. Some of these were used to establish the quality of the individual simulations of the aircraft impact and the fire growth, as described in Sections 6.9 and 6.10. While the agreement between observations and simulation was not exact, the differences were within the uncertainties in the input information. The generally successful comparisons lent credibility to the overall reconstruction of the disaster.

There remained a small, but important number of observations against which the structural collapse sequences could be judged. The comparisons are for Cases B and D impact damage and temperature histories, for which the better agreement was obtained.

Table 6–10. Comparison of global structural model predictions and observations for WTC 1, Case B.

Observation	Simulation
Following the aircraft impact, the tower still stood.	The tower remained upright with significant reserve capacity.
The south perimeter wall was first observed to have bowed inward at 10:23 a.m. The bowing appeared over nearly the entire south face of the 94th to 100th floors. The maximum bowing was 55 in. on the 97th floor. (The central area in available images was obscured by smoke.)	The inward bowing of the south wall at 10:28 a.m. It extended from the 94th to the 100th floor, with a maximum of about 43 in.
As the structural collapse began, the building section above the impact and fire zone tilted at least 8 degrees to the south with no discernable east or west component in the tilt. Dust clouds obscured the view as the building section began to fall downward.	The south side bowed and weakened. The analysis stopped as the initiation of global instability was imminent.
The time to collapse initiation was 102 min from the aircraft impact.	There was significant weakening of the south wall and the core columns. Instability was imminent at 100 min.

Table 6–11. Comparison of global structural model predictions and observations for WTC 2, Case D.

Observation	Simulation
Following the aircraft impact, the tower still stood.	The tower remained upright with significant reserve capacity.
The east perimeter wall was first observed to have bowed inward approximately 10 in. at floor 80 at 9:21 a.m. The bowing extended across most of the east face between the 78th and 83rd floors.	The inward bowing of the east wall had a maximum value of about 9.5 in. at 9:23 a.m. The bowing extended from the 78th floor to the 83rd floor.
The building section above the impact and fire area tilted to the east and south as the structural collapse initiated. The angle was approximately 3 degrees to 4 degrees to the south and 7 degrees to 8 degrees to the east prior to significant downward movement of the upper building section. The tilt to the south did not increase as the upper building section began to fall, but the tilt to the east rose to approximately 25 degrees before dust clouds obscured the view.	At point of instability, there was tilting to the south and east.
The time to collapse initiation was 56 min after the aircraft impact.	The analysis predicted global instability after 43 min.

The agreement between the observations and the simulations is reasonably good, supporting the validity of the probable collapse sequences. The exact times to collapse initiation were sensitive to the factors that controlled the inward bowing of the exterior columns. The sequence of events leading to collapse initiation was not sensitive to these factors.

6.14.9 Factors that Affected Building Performance on September 11, 2001

- The unusually dense spacing of perimeter columns, coupled with deep spandrels, resulted in a robust building that was able to fragment the aircraft upon impact and redistribute loads from severed perimeter columns to adjacent, intact columns.
- The wind loads used for the WTC towers, which governed the design of the framed-tube system, significantly exceeded the requirements of the building codes of the era and were consistent with the independent NIST estimates that were based on current state-of-the-art considerations.
- The robustness of the perimeter framed-tube system and the large lateral dimension of the towers helped the buildings withstand the impact of the aircraft.
- The composite floor system enabled the floors to redistribute loads from places of aircraft impact damage to other locations, avoiding larger scale collapse upon impact.
- The hat truss resisted the significant weakening of the core by redistributing loads form the damaged columns to intact columns.

As a result of these factors, the buildings would likely not have collapsed under the combined effects of the aircraft damage and subsequent fires if the insulation had not been widely dislodged. The thickness and the condition of the insulation prior to aircraft impact did not play a governing role in the initiation of building collapse.

Chapter 7
RECONSTRUCTION OF HUMAN ACTIVITY

7.1 BUILDING OCCUPANTS

7.1.1 Background

While much attention has properly focused on the nearly three thousand people who lost their lives at the World Trade Center (WTC) site that day, the circumstances and efforts that led to the successful evacuation of five times that many people from the WTC towers also have been given attention. Understanding why the loss of life was high or low was one of the four objectives of the Investigation.

Success in clearing a building in an emergency can be characterized by two quantities: the time people need to evacuate and the time available to them to do so. For the WTC towers, the times available for escape were set by the collapse of the buildings. Neither the building occupants nor the emergency responders knew those times in advance. Moreover, the times were also three or four times shorter than the time needed to clear the tenant spaces of WTC 1 following the 1993 bombing.

The investigators examined the design of the buildings, the behavior of the people, and the evacuation process in detail to ascertain the factors that figured prominently in the time needed for evacuation. In analyzing these factors, NIST recognized that there were inherent uncertainties in constructing a valid portrayal of human behavior on that day. These included limitations in the recollections of the people, the need to derive findings from a statistical sampling of the building population, the lack of information from the decedents on the factors that prevented their escape, and the limited knowledge of the damage to the interior of the towers. NIST carefully considered these uncertainties in developing its findings and is confident in those findings and related recommendations.

7.1.2 The Building Egress System

Examination of drawings, memoranda, and calculations showed that the standard emergency evacuation procedures required using the three stairwells. The elevators were not to be used, and the doors to the roof were to be kept locked. Under most circumstances, a local evacuation would be ordered. The people on the floors near the threat would move to three floors below the incident. Under more severe circumstances, a full building evacuation would be ordered, requiring all occupants to leave the building by way of the stairwells.

As noted in Section 1.2.2, the locations of the stairwells differed at various heights in the buildings. This, combined with the aircraft impacting different floors in the two towers, the different aircraft impact location relative to the center of the building, and the different orientation of the core (Section 1.2.2), led to different damage to the stairwells. As shown in Figure 7–1, a frame from a simulation from a NIST contractor, Applied Research Associates (Section 6.9), the stairwell separation in this region of WTC 1 was the smallest in the building—clustered together well within the building core—and American Airlines Flight 11 destroyed all three stairwells from the 92nd floor upward. By contrast, the separation of the stairwells in the impacted region of WTC 2 was the largest in the building, i.e., they were located

along different boundaries of the building core. United Airlines Flight 175 destroyed Stairwells B and C, but not Stairwell A (Figure 7–2).

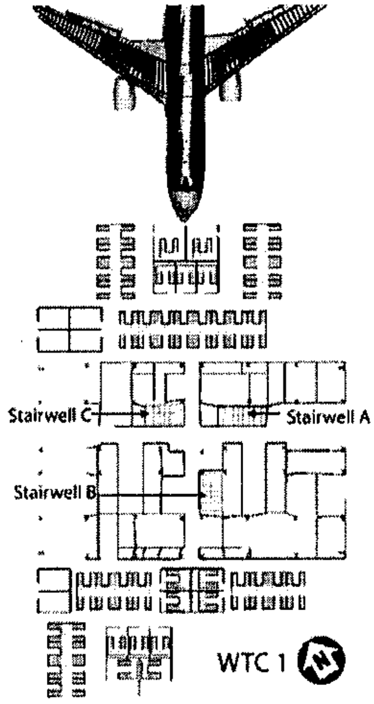


Figure 7–1. Simulated impact damage to 95th floor of WTC 1, including stairwells, 0.7 s after impact.

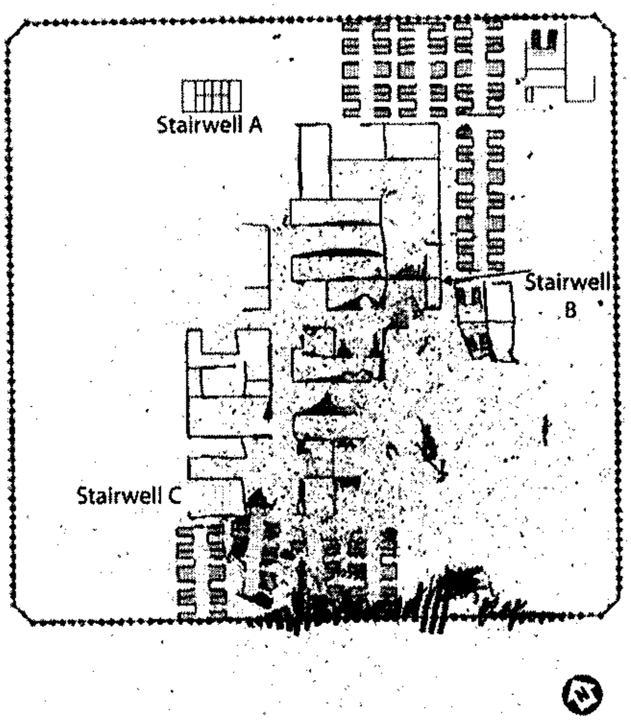


Figure 7–2. Simulated impact damage to WTC 2 on floor 78, 0.62 s after impact.

7.1.3 The Evacuation—Data Sources

To document the egress from the two towers as completely as possible, NIST:

- Contracted with the National Fire Protection Association and the National Research Council of Canada to index a collection of over 700 previously published interviews with WTC survivors.
- Listened to and analyzed 9-1-1 emergency phone calls made during the morning of September 11.
- Analyzed transcripts of emergency communication among building personnel and emergency responders.
- Examined complaints filed with the Occupational Safety and Health Administration by surviving occupants and families of victims regarding emergency preparedness and evacuation system performance.

In addition NIST, in conjunction with NuStats, Partners, LLP as a NIST contractor, conducted an extensive set of interviews with survivors of the disaster and family members of occupants of the buildings. First, telephone interviews were conducted with 803 survivors, randomly selected from the list of approximately 100,000 people who had badges to enter the towers on that morning. The results enabled a scientific projection of the population and distribution of occupants in WTC 1 and WTC 2, as well as exploration of factors that affected evacuation. Second, 225 face-to-face interviews, averaging 2 hours each, gathered detailed, first-hand accounts and observations of the activities and events inside the buildings on the morning of September 11. These people included occupants near the floors of impact, witnesses to fireballs, mobility-impaired occupants, floor wardens, building personnel with emergency response responsibilities, family members who spoke to an occupant after 8:46 a.m., and occupants from regions of the building not addressed by other groups. Third, six complementary focus groups, a total of 28 people, were convened, consisting of:

1. Occupants located near the floors of impact, to explore the extent of the building damage and how the damage influenced the evacuation process.
2. Floor wardens, to explore the implementation of the floor warden procedures and the effect those actions had on the evacuation of the occupants on a floor and the evacuation of the floor warden.
3. Mobility-impaired occupants, to explore the effect of a disability on the evacuation of the occupant and any other individuals who may have assisted or otherwise been affected by the evacuee.
4. Persons with building responsibilities, to capture the unique perspective of custodians, security, maintenance, or other building staff.

5. Randomly selected evacuees in WTC 1, to explore further the variables that best explained evacuation delay and normalized stairwell evacuation time, including environmental cues, floor, and activities.

6. Randomly selected evacuees in WTC 2, for the same purpose as the preceding group.

The following sections describe the key findings from this large data set.

7.1.4 Occupant Demographics

The following were estimated from statistical analysis of the telephone interview data:

- There were 17,400 ± 1,180 occupants inside WTC 1 and WTC 2 at 8:46 a.m. Of these, 8,900 ± 750 were inside WTC 1 and 8,540 ± 920 were inside WTC 2.
- Men outnumbered women roughly two to one.
- The mean and median ages were both about 45, with the distribution ranging from the early 20s to the late 80s.
- The mean length of employment at the WTC was almost six years, but the median was only two years tenure within WTC 1 and three years within WTC 2.
- Sixteen percent of the evacuees were present during the 1993 bombing, although many others knew of the evacuation.
- Two-thirds had participated in at least one fire drill in the 12 months prior to the 2001 disaster. Eighteen percent did not recall whether they had participated or not; 18 percent reported that they had not. New York City law prohibited requiring full evacuation using the stairs during fire drills.
- Six percent reported having a limitation that constrained their ability to escape. (This extrapolated to roughly 1,000 of the WTC 1 and WTC 2 survivors.) The most common of these limitations, in decreasing order, were recent injury, chronic illness, and use of medications.

Estimates based on the layouts of the tenant spaces indicated that approximately 20,000 people worked in each tower. Relatively few visitors would have been present at 8:46 a.m. Thus, the towers were between one-third and one-half full at the time of the attack.

7.1.5 Evacuation of WTC 1

The number of survivors evacuated from WTC 1 was large, given the severity of the building damage and the unexpectedly short available time. Of those who were below the impact floors when the aircraft struck, 99 percent survived. About 84 percent of all the occupants of the tower at the time survived. The aircraft impact damage left no exit path for those who were above the 91st floor. It is not known how many of those could have been saved had the building not collapsed. While it is possible that a delayed

or avoided collapse could have improved the outcome, it would have taken many hours for the FDNY to reach the 92nd floor and higher and then to conduct rescue and fire suppression activity there.

The general pattern of the evacuation was described in Chapter 2. The following are specific facts derived from the interviews:

- The median time to initiate evacuation was 3 min for occupants from the ground floor to floor 76, and 5 min for occupants near the impact region (floors 77 through 91). The factors that best explained the evacuation initiation delays were the floor the respondent was on when WTC 1 was attacked, whether the occupant encountered smoke, damage or fire, and whether he or she sought additional information about what was happening.

- Occupants throughout the building observed various types of impact indicators throughout the building, including wall, partition, and ceiling damage and fire and smoke conditions. The filled-in squares in Figure 7–3 indicate the floors on which the different observations were reported.

- Damage to critical communications hardware likely prevented announcement transmission, and thus occupants did not hear announcements to evacuate, despite repeated attempts from the lobby fire command station.

- Evacuation rates reached a maximum in approximately 5 min, and remained roughly constant until the collapse of WTC 2, when the rate in WTC 1 slowed to about 20 percent of the maximum.

- The maximum downward travel rate was just over one floor per minute, slower than the slowest speed measured for non-emergency evacuations. This was in part because:

  - Occupants encountered smoke and/or damage during evacuation.

  - Occupants were often unprepared for the physical challenge of full building evacuation.

  - Occupants were not prepared to encounter transfer hallways during the descent.

  - Mobility-impaired occupants were not universally identified or prepared for full building evacuation.

  - Occupants interrupted their evacuation.

- The mobility-impaired occupants did not evacuate as evenly as the general population.

  - Those who were ambulatory generally walked down the stairs with one hand on each handrail, taking one step at a time. They were typically accompanied by another occupant or an emergency responder. Combined, they blocked others behind them from moving more rapidly.

  - On the 12th floor, FDNY personnel found 40 to 60 people, some of whom were mobility impaired. The emergency responders were assisting about 20 of these mobility-impaired

people down the stairs just prior to the collapse of the building. It is unknown how many of this group survived.

- Some mobility-impaired occupants requiring assistance to evacuate were left by coworkers, thereby imposing on strangers for assistance.

7.1.6 Evacuation of WTC 2

The evacuation from WTC 2 was markedly different from that from WTC 1. Over 90 percent of the occupants had started to self-evacuate before the second aircraft struck, and three-quarters of those from above the 78th floor had descended below the impact region prior to the second attack. (Nearly 3,000 occupants were able to survive due to self-evacuation and the use of the still-functioning elevators.) As a result, 91 percent of all the occupants survived. Eleven people from below the impact floors perished, about 0.1 percent. Eighteen people in or above the impact zone when the plane struck are known to have found the one passable stairway and escaped. It is not known how many others from the impact floors or above found their way to the passable stairway and did not make it out or how many could have been saved had the building not collapsed. A delayed or avoided collapse could have provided the additional time for more people to learn about and use the passable stairway.

The general pattern of the evacuation was described in Chapter 3. The following are specific facts derived from the interviews:

- The median time to initiate evacuation was 6 min, somewhat longer than in WTC 1.
- As in WTC 1, occupants observed various types of impact indicators throughout the building, including wall, partition, and ceiling damage and fire and smoke conditions (Figure 7–4).
- Building announcements were cited by many as a constraint to their evacuation, principally due to the 9:00 a.m. announcement instructing occupants to return to their work spaces. Crowdedness in the stairways, lack of instructions and information, as well as injured or disabled evacuees in the stairwells were the most frequently reported obstacles to evacuation.
- Evacuation rates from WTC 2 showed three distinct phases:

  (1) Before WTC 2 was attacked, occupants used elevators, as well as stairs, to evacuate, resulting in approximately 40 percent of the eventual survivors leaving the building during that 16 min window.

  (2) After WTC 2 was attacked and the elevators were no longer operational, the evacuation rate slowed down to a steady rate equivalent to the rate observed in WTC 1, which also had only stairs available to occupants.

  (3) About 20 min prior to building collapse, the rate in WTC 2 slowed to approximately 20 percent of the stairwell-only evacuation rate.

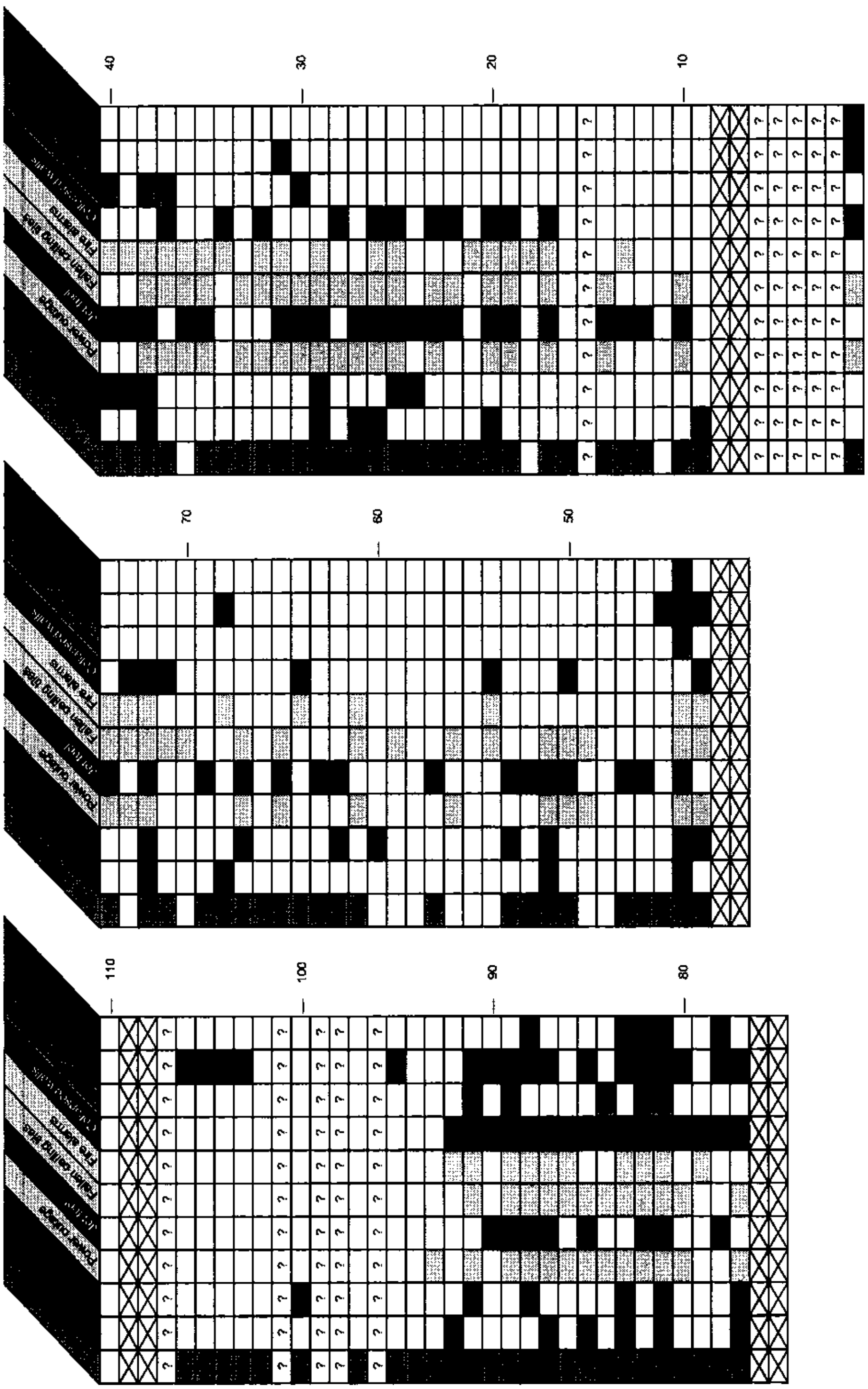


Figure 7–3. Observations of building damage after initial awareness but before beginning evacuation in WTC 1.

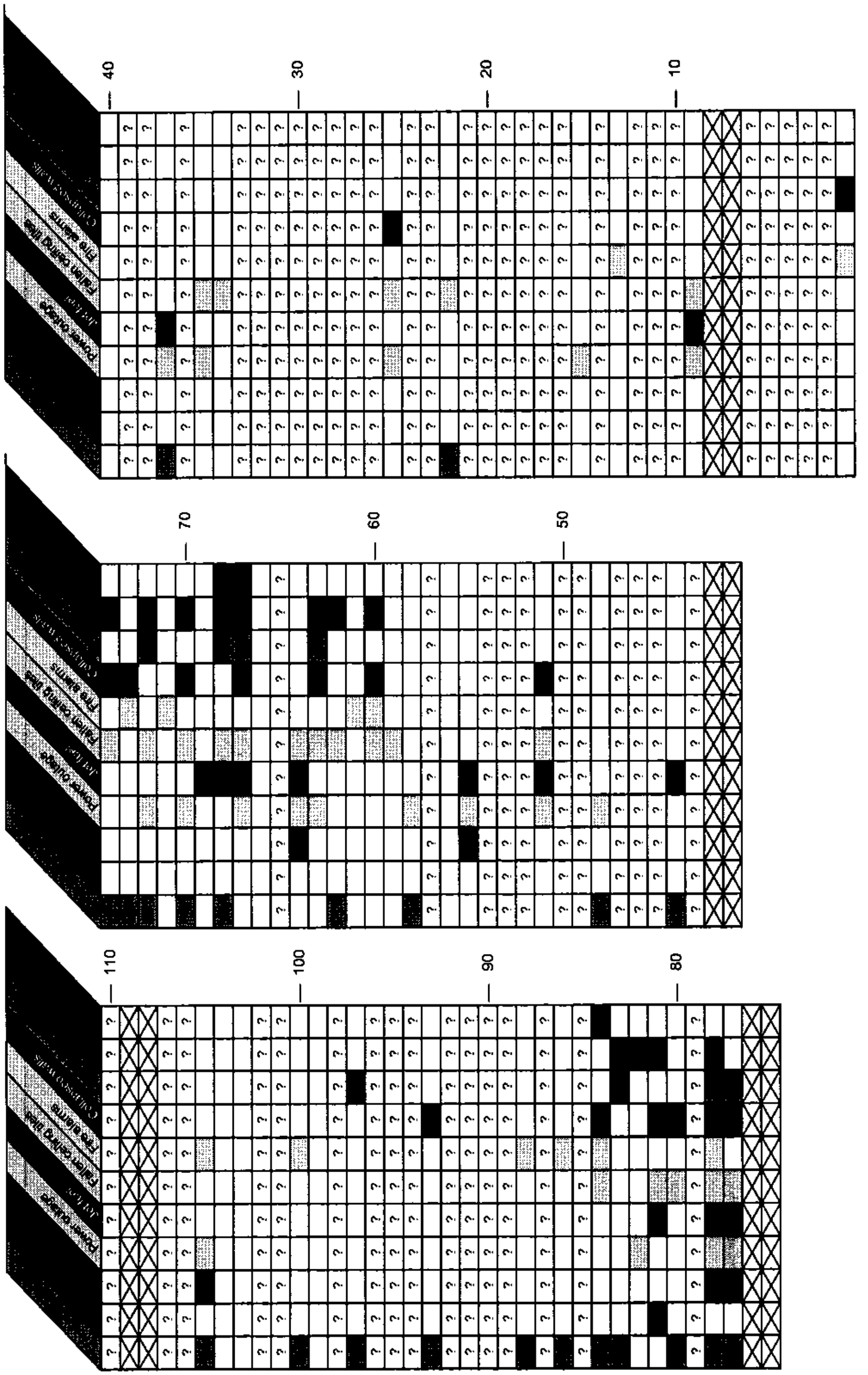


Figure 7–4. Observations of building damage from tenant spaces in WTC 2.

7.2 EMERGENCY RESPONDERS

7.2.1 Data Gathered

The attack on the World Trade Center produced a massive response from the emergency services within New York City. As a result, copious information was produced concerning the attack and the emergency response. Although some key information was lost when the buildings collapsed, an extensive amount was obtained from three organizations that contributed to the emergency response: The Port Authority of New York and New Jersey (Port Authority), FDNY, and the New York City Police Department (NYPD). There also was a significant amount of information available through the various media services. Some of the items were transferred to NIST; the Investigation Team examined others at locations in the New York City area. The data fell into four categories.

Documentary Data

This included procedures for conducting operations at the WTC, records generated during the WTC operations, and records generated following the event. The last group of documents included detailed investigative reports of the FDNY and NYPD operations by McKinsey and Company, documents of investigative first-person interviews, and lists of decedents.

Electronic Data

These were recordings of radio and telephone communications. Some were already in digital format; those on tape were digitized and/or transcribed. Some recordings required sound enhancement to improve comprehension.

First-Person Interviews

In October 2003, NIST entered into a three-party agreement between NIST, New York City (NYC), and the National Commission on Terrorist Acts Upon the United States (the 9/11 Commission). The agreement provided procedures under which NIST and the 9/11 Commission would interview a maximum of 125 NYC emergency responders, 100 from FDNY and 25 from NYPD. In December 2003, NIST officially requested and the Port Authority agreed to interviews with 15 Port Authority personnel, including emergency responders, safety, security, and management personnel. In addition to the interviews conducted under the agreements described above, NIST interviewed eight people who contacted NIST directly and volunteered. The first-person interviews were conducted beginning in October 2003 and were completed in December 2004.

The organizations and the number of interviews conducted were:

- FDNY (68 interviews): Senior management and officers, mid-level officers, company officers, firefighters, emergency medical personnel, and dispatchers
- NYPD (25 interviews): Senior management and officers, mid-level officers, Emergency Service Unit personnel, aviation personnel, and dispatchers

- PANYNJ/PAPD (15 interviews): Senior management personnel, facility safety personnel, building security personnel, facility communications personnel, building vertical transportation personnel, senior PAPD officers, mid-level PAPD officers, and line PAPD officers

- Other (8 interviews): A building security guard, dispatcher, firefighters, WTC building engineer, and a fire safety director

Each interview generally took from 1 hour to 4 hours to complete, depending on the person's job and the complexity of their involvement in emergency operations.

An interview included a self-narrative regarding the emergency responder's experience at the WTC and follow-up questions by staff from NIST and the 9/11 Commission.

Visual Data

These still photographs and video footage became part of the collection described in Section 6.3.

7.2.2 Operation Changes following the WTC 1 Bombing on February 26, 1993

This unprecedented act had provided insight into the complex nature of responding to a large incident at the WTC towers. As a result, numerous issues were raised concerning the WTC buildings in relationship to the emergency response. A multiagency study identified issues of security, occupant safety, and emergency responder operations and safety. The following changes made by The Port Authority and the FDNY had a direct impact on emergency responder operations on September 11, 2001.

The Port Authority

- Improved egress from the towers at the Concourse Level.

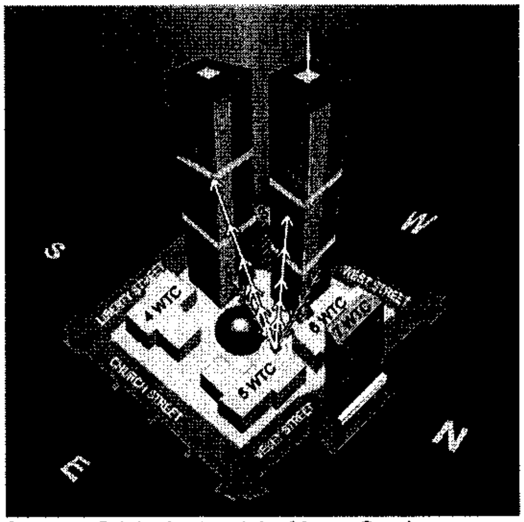
- Made improvements to the stairwells: battery operated emergency lighting, photoluminescent floor strips indicating the path to be followed, and explicit signs on each doorway to indicate where it led.

- Established a PAPD Command Center inside of WTC 5.

- Installed Fire Command Desks in the lobbies of WTC 1 and WTC 2.

- Installed in WTC 5 a radio repeater that operated on the FDNY city-wide high-rise frequency. (The radio repeater's function was to receive FDNY radio communication on a specified radio frequency, amplify the signal power, and retransmit the radio communications on another specified radio frequency that the FDNY radios could receive. This could enhance communications in buildings made of steel and reinforced concrete that pose challenges to radio-frequency communication.) The antenna was located on the top of WTC 5 and was directed at WTC 1 and WTC 2 (Figure 7–5). On September 11, 2001, the controls for operating the repeater were located at the Fire Command Desks in the tower lobbies.

- Upgraded the elevator intercom system to be monitored at the lobby Fire Command Desks.
- Constructed an Operations Control Center on the B1 level of WTC 2 with the capability to monitor all HVAC systems and elevators.
- Installed a decentralized fire alarm system, with three separate data risers to transponders located every three floors, redundant control panels and electronics, and multiple control station announcement capability.
- Conducted fire drills in conjunction with FDNY.



Source: Original artwork by Marco Crupi. Enhanced by NIST.

Figure 7–5. Location of the radio repeater.

FDNY

- Published a new Incident Command System manual in May 1997.
- Purchased eighty 800 MHz radios for use by deputy fire commissioners, each staff chief, and the Field Communications Unit. Twenty of the radios were to be distributed by the Field Communications unit at an incident, if needed.
- Issued Port Authority radios to those FDNY companies located near the WTC that often responded to the WTC, allowing them to communicate with the building's Deputy Fire Safety Directors and with PAPD.

In addition, The Port Authority and New York City signed two agreements applying to the fire safety of Port Authority facilities located in New York City. The first agreement was for the implementation of fire safety recommendations that would be made by FDNY after they had inspected Port Authority facilities located in New York City. The second recognized the agreement that FDNY could conduct fire safety inspections of Port Authority properties in New York City. It provided guidelines for FDNY to communicate needed corrective actions to The Port Authority, and it assured that new or modified fire safety systems were to be in compliance with local codes and regulations. It also required a third party review of the systems by a New York State licensed architect or engineer.

7.2.3 Responder Organization

The emergency response to the attack was immediate. Within 3 min of the aircraft impact on WTC 1, PAPD was providing information on the attack to the police desk, FDNY had dispatched 26 units to the scene, and NYPD had called a department mobilization that included dispatching aviation units to the WTC for visual assessment. Within 10 min, PAPD had called a chemical mobilization; NYPD had dispatched five Emergency Service Unit (ESU) teams and had two aviation units at the scene providing observations. Within 30 min, 121 FDNY units had been dispatched to the scene and 30 units had signaled their arrival at the scene by pushing the "10-84" button on the vehicle's communications console (Figure 7–6).

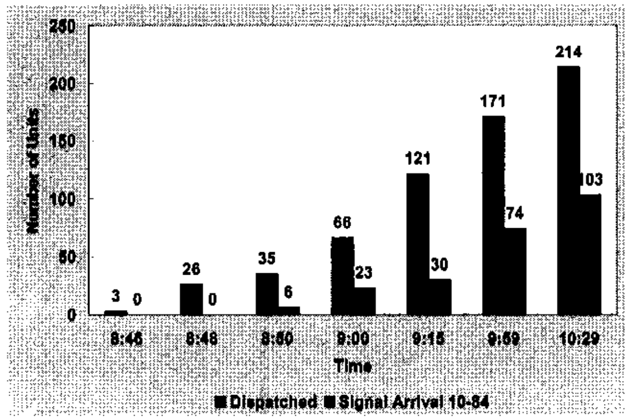


Figure 7–6. Timing of FDNY unit arrivals.

FDNY

Under New York City policy, since this was identified as a fire incident, FDNY was to be in control of the site. By 8:50, FDNY was operating from the Fire Command Desk in the lobby of WTC 1. Within minutes, the Incident Command Post was moved outside to West Street. The FDNY also maintained the lobby Command Post inside WTC 1 and established one in WTC 2. Additional command posts were established in the lobby of the Marriott Hotel (WTC 3) and on the corner of West and Liberty Streets.

Some of the first FDNY personnel on the scene had actually seen the aircraft hit the building and knew that the upper floors were badly damaged, including the building safety systems. They also saw the victims burned by the fireball that came into the building lobby. Upon meeting with Port Authority personnel and the previous WTC 1 Deputy Fire Safety Director, who had recently trained the new Fire Safety Director, to learn more about building conditions, FDNY personnel quickly made judgments related to building conditions and emergency response operations that were, in retrospect, highly accurate, for example:

- There were large fires burning on multiple floors at and above the impact zone.
- Smoke, fire, and structural damage in the buildings prevented many building occupants from evacuating floors above the impact zones.
- Many of the people trapped above the impact zones were already dead or would likely die before emergency responders could reach them.
- Localized collapses within and above the impact zones were possible due to the structural damage and fires.

- The elevators, some with people trapped inside, were generally not working and/or were not safe for use during the WTC operations.

- Firefighters would have to gain access to the injured and trapped occupants by climbing the stairs and carrying the equipment needed up the stairs.

- It would take hours to accumulate sufficient people and equipment to access the impact zones.

- The sprinkler and standpipe systems were compromised at the impact zone and firefighting would not be an option until a reliable water supply was established and equipment was carried up.

- Jet fuel had flowed into the elevator shafts and into other parts of the buildings and presented a danger to building occupants and emergency responder personnel.

Those in command decided that the response strategy was to enable the evacuation of those below the impact and fire zones. However, those directing initial operations inside the buildings followed an additional strategy: get sufficient people and equipment upstairs to cut a path through the fire and debris to rescue occupants above the fires. The strategy of company-level personnel, who were trained to fight fires and perceived this as a conventional, large high-rise fire, was to get to the fire floors and extinguish the fires.

Overlaying this trinity of operational strategies was the fact that this was the largest emergency response in FDNY history, with roughly 1,000 firefighters on the scene. Even the singularly large response to the 1993 bombing involved about 700 emergency personnel. A typical two-alarm fire might have involved about 100 personnel.

Thus, keeping track of what all these people were doing, where there were located, where they were going, and what they would do when they got there was a task without precedent. The principal tools for this were three 18 in. x 28 in. magnetic boards known as Fire Command Boards (Figure 7–7). They were located in the lobbies of WTC 1 and WTC 2 and at the Incident command Post on West Street. On each Board, magnetic identifiers of different colors identified engines, ladder and tower ladders, battalions, special units, and sectors. Unit numbers were written on the identifiers with marking pens. These Boards became overwhelmed after about 30 min due to the large number of people and units arriving at the scene. Some emergency personnel that arrived at the site did not report to the Command Posts or were not logged in on the Command Board. A formal analysis of arrivals and missions of the various units was compromised by the loss of the Boards in the collapse of the towers; there were no backup records.

NYPD

The roles of the NYPD were to establish traffic control and perimeter security at the site, provide security for the command posts, and conduct evacuation and rescue operations within the towers. Their aviation units supplied observation capability and assessed the potential for roof rescue.

The primary mobilization point for the NYPD Special Operations Division (SOD) that sent Emergency Service Unit (ESU) rescue teams into the WTC was at the corner of Church and Vesey Streets at the

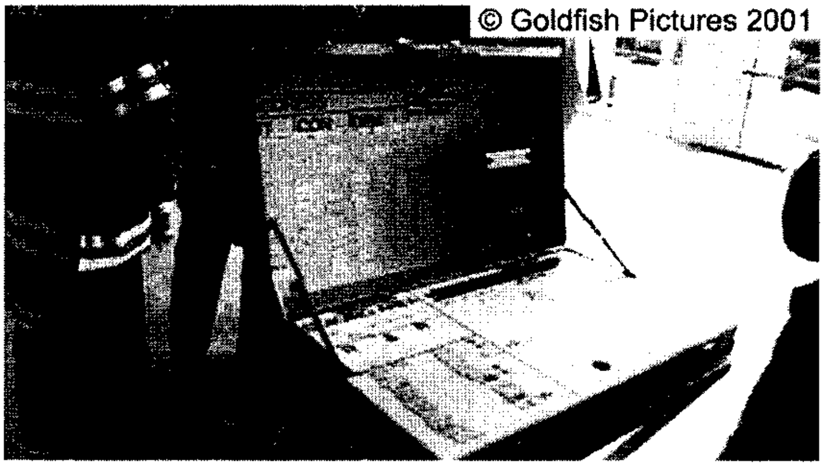


Figure 7–7. Fire Command Board located in the lobby of WTC 1.

northeast corner of the WTC tract. The post was managed by a SOD detective who had just gone off of duty and was still at his office when the attack occurred. He dispatched six ESU teams, each consisting of about five people. Records for each team were written on paper attached to a clipboard.

A second SOD mobilization point was established at the corner of West and Vesey Streets at the northwest corner of the WTC tract. The armed NYPD officers and ESU teams provided security for the FDNY Incident Command Post.

Since there were few NYPD units and since they typically arrived with all members, keeping track of the units was less problematic than for the FDNY. However, with the collapse of WTC 2, all written records were lost as the high winds and debris blew through the mobilization points. Since NYPD had only about 50 personnel operating in or near the towers, the managers of the mobilization points were able to easily reconstruct the lost data on their personnel.

Although The Port Authority had not endorsed a plan for roof rescue from the towers, it appeared to be one of the few options available for occupants trapped above the fires. NYPD helicopters reached the scene by 8:52 to assess the possibility of roof rescue. They were unable to land on the roof due to heavy smoke conditions. During the first hour, FDNY did not consider the option of roof rescue. When the aircraft struck WTC 2, it was clear that this was criminal activity, and the decision regarding roof top operations became the responsibility of NYPD. The NYPD First Deputy Commissioner ordered that no roof rescues were to be attempted, and at 9:43 a.m., this directive was passed to all units.

Roof rescue was not intended to be an option, and The Port Authority reported that it never advised tenants to evacuate upward. The Port Authority's standard full-building occupant evacuation procedures and drills required the use of stairways to exit at the bottom of the WTC towers. The standard procedures were to keep the doors to the roof locked. Roof access required use of an electronic swipe card to get through the first two doors and a security officer watching a closed-circuit camera on the 22nd floor of WTC 1 to open the third door via a buzzer. (The 1968 NYC Building Code required access to roofs like these, most likely to provide FDNY access. The 2003 code does not intend roof access to be used for evacuation and has no prohibition on locking this access.)

The NYPD and FDNY did not consider roof rescue a viable strategy for general evacuation. First, the NYPD and FDNY policies for roof operations were focused mainly on providing emergency responders with access into the building above the fire floors for firefighting, conventional rescue, and comforting occupants. Roof rescue was considered a measure of last resort to be used, for example, to assist occupants with medical emergencies. Second, although on September 11, an NYPD aviation unit was early on the scene to consider the possibility, smoke and heat conditions at the top of the towers prevented the conduct of safe roof operations, despite repeated attempts. Even if it had been possible for a helicopter to gain access to the roof, only a very small fraction of the large number of people trapped above the impact zone could have been rescued before the towers collapsed. Nonetheless, perhaps as an indication of the dire situation in the top floors of the towers, at least two decedents tried to get to the roof and found the roof access locked in both the WTC towers. Personnel at the WTC 1 Security Control Center on the 22nd floor attempted to electronically release the doors to the roof, but were unsuccessful due to damage to the computerized control system.

PAPD

The roles of the PAPD were to establish security at the WTC and to conduct evacuation operations.

PAPD officers were performing their normal law enforcement duties at the WTC site when the attack on WTC 1 occurred. Several additional PAPD teams were dispatched from various locations from around the city and from Jersey City, with some arriving before the collapse of WTC 2 and reporting to PAPD personnel at the WTC 1 lobby Fire Command Desk. There were dozens of PAPD officers on site and on orders to report to the site. With the collapse of WTC 2, the PAPD Police Desk (in WTC 5) and the Command Center were evacuated. Many of the emergency response records were lost initially, but were recovered some days later.

Interdepartmental Interactions

The coordination of communications and operations between the responding authorities at the WTC site was a challenge for all emergency responders working that morning. The short time duration between the initial attack and the collapse of the towers, coupled with the large number of responders and their staggered arrivals, compounded the difficulty of establishing a unified operation.

FDNY (and the Emergency Medical Services), NYPD, PAPD, The Port Authority, and OEM were attempting to work together. These efforts were stymied by a lack of existing protocols that clearly defined authorities and responsibilities, communications systems problems, and multiple major attacks and threats. Although there was merit to having the FDNY and NYPD Command Posts separated, there was no uniform means for communicating between the two Command Posts at the time when WTC 2 collapsed. FDNY and NYPD were primarily operating as independent organizations based on their operational responsibilities.

7.2.4 Responder Access

Fighting fires in the upper levels of tall buildings is not the same as fighting fires in buildings that are less than 100 ft high. In the case of the WTC towers, the people needing assistance were mostly many stories above the ground, and climbing tens of flights of stairs was the only way upward for the emergency

responders. In the time available, they were not able to get very far. For example, emergency responders wearing police uniforms, not wearing Self-contained Breathing Apparatus (SCBA), and not carrying extra equipment, were able to climb the stairs at a rate of approximately 1.4 min per floor while climbing to floors in the 40s inside of WTC 1. The climbing rate for firefighters wearing protective clothing and SCBA and carrying extra firefighting and rescue equipment was about 2 min per floor. The downward flow of evacuees, especially those who had physical disabilities or were obese, also slowed the responders' progress, especially in the 44 in. wide stairwells. The flow of the evacuees caused teams of emergency responders to become separated, further disrupting team operations.

Neither the number of responders who entered the towers nor the floors they reached are known, due to the incompleteness of the Command Boards and their eventual destruction. From radio communications and first-person interviews, it appears that there were responders as high as floors in the 50s in WTC 1 and the 78th floor in WTC 2.

7.2.5 Communications

There were multiple equipment systems for command-to-field communications, for responders to communicate among themselves, and for contact to and from building occupants:

- Landline telephone system (including access to the 9-1-1 system),
- Emergency announcement systems within WTC 1 and WTC 2,
- Cellular systems (including access to the 9-1-1 system),
- Warden phones (tower stair landings to Command Post),
- Firefighter phones, called standpipe phones, in the WTC towers, and
- FDNY handie-talkies, with booster support from a repeaters on WTC 5 and a Battalion car repeater located inside WTC 2.

Within WTC 1, the system used to make the emergency announcements was disabled by the first aircraft impact, communications to the elevators in the upper third of the buildings were lost, the Warden phones did not work, and attempts to use the landline phones to contact people upstairs were unsuccessful due to the failure of some phones in the building.

Little is known about the function of the internal communications inside WTC 2 after the aircraft struck the building. This is because all of the key emergency responders working inside WTC 2 died when the building collapsed. However, interviews with some occupants who evacuated from the building and interviews with emergency responders who communicated with counterparts inside WTC 2 indicated the following: some of the building's public address systems were working, some of the elevator phone systems were working, and some of the landline telephones were working. It is not known if the Warden Phone system was fully operational or if the standpipe phones were operational. Emergency responder communications inside WTC 2 primarily depended on radio and face-to-face communications.